NATIONAL ENERGY TECHNOLOGY LABORATORY

Research Portfolio Accomplishment Report

Unconventional Oil & Gas Resources: Produced Water Treatment & Management

DOE/NETL-2015/1692
Activity 4003.200.03

U.S. DEPARTMENT OF ENERGY

DISCLAIMER

Cover image: **Western Research Institute treating and reusing coal-bed methane (CBM) produced water.**

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The project data, photos, and graphics provided in the project summaries that follow the introduction come from available project documentation—including final reports, fact sheets, NETL project summaries, RPSEA monthly reports, and project websites—and through the generous assistance of Principal Investigators, industry partners, RPSEA, and NETL staff.

Unconventional Oil & Gas Resources:

Produced Water Treatment & Management

Executive Summary

The last decade of research and development (R&D) on produced water treatment and water management, sponsored by the U.S. Department of Energy's (DOE) Office of Fossil Energy, has played an important role in protecting the environment during drilling, completion and production of natural gas and oil from tight sands and shales. Significant achievements include **databases and tools to identify potential risks**, predict possible impacts associated with unconventional resource development, and provide information about beneficial uses of produced water; **data sets** that detail the composition of fluids produced during hydraulic fracturing; **innovative laboratory and field experiments** that led to insights into relevant biochemical, geochemical, and geophysical characterizations of fluid and geology and the development of **novel technologies**; successful **field demonstrations** of environmentally-sound technologies that reduce cost while improving recovery efficiency; and **technology transfer** for commercialization of scalable systems. The R&D efforts of DOE, industry and others focused on unconventional resources have yielded demonstrable, measurable results that have **pushed the U.S. to the global forefront** in the production of natural gas from shale formations, **increased revenues** for states and the federal government, **created** numerous high-paying **domestic jobs**, and **bolstered U.S. universities and industry** as they create the future of energy technology.

R&D efforts in unconventional oil and gas research—including produced water treatment and management research—have pushed the U.S. to the forefront in the production of natural gas from shale formations.

Tens of thousands of wells are drilled and completed in unconventional oil and gas resources (shales and tight sands) each year. Each well requires millions of gallons of water for drilling and hydraulic fracturing activities. An inextricable part of the process is also the production of water that must be treated and disposed—that produced water is the largest volume waste stream associated with hydrocarbon recovery. The 100,000-member Society of Petroleum Engineers has identified Water Management as one of five major R&D challenges facing the oil and gas industry.

Increasingly stringent environmental regulations require exten-

sive treatment of produced water from oil and gas operations before discharge. Treatment and disposal of such volumes costs the industry more than $40 billion annually. Consequently, for oil and gas production wells located in water-scarce regions, limited freshwater resources in conjunction with the high treatment cost for produced water discharge makes beneficial reuse of produced water an attractive opportunity. Other challenges associated with water treatment and management have been identified, and include poorly documented water and water flow back characteristics, inadequately described disposal options in geologic basins, and difficult or expensive technology for processing high salinity water.

The public also has concerns over the use of fresh water resources, especially in arid and drought-stricken areas; the contamination of fresh water resources on both the surface and in aquifers; and ancillary effects such as truck traffic and related environmental, noise, and health impacts.

The DOE's National Energy Technology Laboratory (NETL) began addressing these concerns in earnest around 2008. The effort includes research funded through annual appropriations under the Environmentally Prudent Development Program, research initiated through Section 999 of the Energy Policy Act of 2005 (Section 999), aka the Ultra-Deepwater and Unconventional Natural Gas and Other Petroleum Resources Research Program, and research conducted through NETL's Office of Research and Development (ORD). Safety and the reduction of environmental impacts have been key elements of this research. R&D focuses on protecting groundwater and air quality, understanding rock and fluid interactions, and integrating environmental protection which includes water treatment technologies and water management. Completed, ongoing and future R&D will continue to reduce the environmental footprint associated with developing unconventional resources to ensure sustainable development over time.

The Environmentally Prudent Development (EPD) Program focuses on advancing national research goals through science and technology development conducted in partnership with other federal agencies, national laboratories, and the private sector. The research program is aligned with the research priorities as described in "Federal Multi-agency Collaboration on Unconventional Oil and Gas Research" that was jointly released by the DOE, the USGS, and the EPA in July 2014. The goal of the EPD Program is to support the prudent development of the nation's shale gas, tight gas, and tight oil resources (collectively referred to as "Unconventional Oil and Gas ("UOG") resources") by 1) increasing our understanding of the varied nature of subsurface processes acting during development, 2) enabling the more efficient utilization of resources via technology that allows greater recovery from fewer, less impactful, wells, and 3) providing objective science and technological solutions that mitigate the environmental risks associated with UOG development.

This report highlights many of the accomplishments achieved by projects focused on produced water treatment and water management through partnerships between DOE, industry, and academia. For example:

- The Risk Based Data Management System (RBDMS) and FracFocus chemical disclosure registry are available online and provide the public, industry professionals, and regulatory agencies with access to information on oil and natural gas activities.
- Altela, Inc.'s AltelaRain® water desalination system was successfully demonstrated and is now turning produced water from shale gas development in the Marcellus Shale into clean water, ready for reuse or discharge.
- A new framework, *Produced Water Treatment Beneficial Use Screening Tool,* provides industry with tailored suggestions for water treatment and management options.
- New coatings for ultrafiltration and reverse osmosis membranes doubled membrane life while reducing the energy demands of produced water treatment.

Additional details on these and other accomplishments are provided in the sections that follow in this report.

Image caption: Wetland created by discharge of coal-bed natural gas produced water.

Introduction

The goal of the EPD Program is to support the prudent development of the nation's shale gas, tight gas, and tight oil resources by 1) increasing our understanding of the varied nature of subsurface processes acting during development, 2) enabling the more efficient utilization of resources via technology that allows greater recovery from fewer, less impactful, wells, and 3) providing objective science and technological solutions that mitigate the environmental risks associated with UOG development. The research projects within the portfolio have been categorized into "bins" of projects that are focused on a common topic. This Research Portfolio Accomplishment Report provides a snapshot of accomplishments to-date for active and completed projects that are grouped into the Produced Water Treatment and Management bin. The first section of this report provides an overview of the bin. Project summaries for each of the projects are provided in the pages that follow.

What is produced water treatment and management research?

Produced water treatment and management research comprises the development of methods for tracing produced water flow, developing novel water treatment technologies, and creating and implementing beneficial uses for produced water. To accomplish this, cross-cutting research brings together technical expertise in materials science, physics, chemistry, geology, engineering, computer modeling, and other oil and gas technologies to improve current disposal and treatment options. Produced water treatment and management R&D also investigates meth-

Risk Based Data Management System and Cost Effective Regulatory Approaches Related to Hydraulic Fracturing and Geologic Sequestration of CO_2

Through partnerships between DOE, the Groundwater Protection Council, and various states, the Risk Based Data Management System (RBDMS) and FracFocus chemical disclosure registry are available online and allow the public, industry professionals, and regulatory agencies to access information on oil and natural gas activities. This access creates transparency and builds public confidence in addition to offering an unparalleled opportunity for improved environmental compliance.

Image caption: **FracFocus is the national hydraulic fracturing chemical registry.**

The RBDMS provides benefits that include the ability to assess and reduce risks to drinking water, the use of non-proprietary software, access to legacy databases, and adaptability to variations oil and gas regulatory and production accounting methods. The tools streamline permitting, reduce the cost of environmental compliance, and provide user-friendly online reporting techniques. Components of the RBDMS provide strategies to prioritize long-term development and implementation.

Additional details about this project are available on p. 51.

ods that ensure beneficial re-use of waste streams, supplement fresh water resources, and mitigate environmental impacts.

The major areas of focus in this research bin include:

- developing cost-effective methods for the treatment and sustainable beneficial use of produced water,
- developing cost-effective methods to handle produced water and control fines,
- developing techniques to minimize the volume of water produced to the surface,
- developing improved approaches for cost-effective disposal of produced water, and
- extending the commercial life of producing unconventional gas and oil wells through reduction of costs associated with water disposal and management.

Why conduct this research?

Produced water treatment and management research helps develop the tools, techniques, and methods to characterize, treat, and/or minimize the volume of produced water so it can be economically managed for beneficial reuse and safe disposal. This research will substantially decrease the environmental impact associated with the production of gas and oil from unconventional resources and reduce the risk of potential negative impact on our nation's potable water supplies.

DOE creates and supports partnerships that drive the development of new technologies, data sets, and methodologies; coordinates complementary research; and fosters the transfer of technologies for commercialization. The demonstration of new technologies may help ease growing public concerns about the impact of UOG development on the environment, which, in turn, may accelerate the scaled-up use and commercialization of the technologies.

Accomplishments

Accomplishments from produced water treatment and management research include novel technologies and predictive models that provide valuable contributions to industry. A number of the projects in the Produced Water Treatment and Management bin have been completed and the project deliverables submitted.

The following selected examples of accomplishments recorded by these research projects illustrate how they are influencing UOG development.

- ***Integrated Produced Water and Management Framework*** – A new framework, Produced Water Treatment Beneficial Use Screening Tool, created by Colorado School of Mines provides industry with tailored suggestions for water treatment and management options. This tool takes site-specific data provided by operators and generates a range of available produced water and management options. This tool will significantly improve the decision-making process for operators by helping them to select the most-effective treatment option.

NORM Mitigation and Clean Water Recovery from Marcellus Frac Water

A pretreatment process resulted in salt crystals with naturally-occurring radioactive materials (NORM) activity low enough for the recovered crystals to be beneficially reused in Pennsylvania or disposed of at a nonhazardous solid waste landfill without further treatment.

Additional details about this project are available on p. 19.

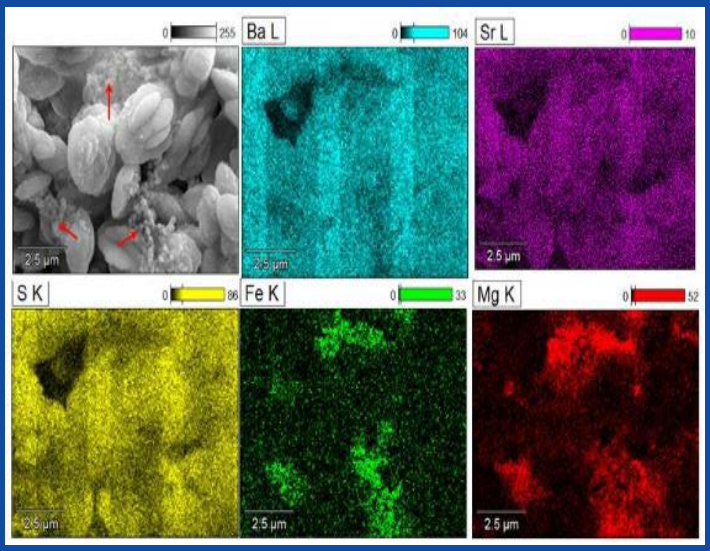


Image caption: **Scanning electron microscope (SEM) image and energy-dispersive X-ray spectroscopy (EDS) elemental maps of sulfate sludge: 50 ppm/v AE1700 (20 mL scale).**

- ***Innovative Membrane Coatings to Lengthen Membrane Life and Reduce Cost*** – The Gas Technology Institute and its partners created new coatings for ultrafiltration and reverse osmosis membranes. These new coatings enabled the team to double membrane life while reducing the energy demands of produced water treatment by more than 35 percent which also reduces cost. Membranes allow operators to recycle and reuse produced water rather than using freshwater; the improved membranes created through this project have the potential to significantly improve the cost-effectiveness of produced water recycling over traditional membranes.

Produced water treatment and management research seeks to protect fresh water resources and address industry's disposal and treatment challenges.

- ***Impact on Crop Yields of Treated Produced Water Irrigation*** – The University of Wyoming studied the impact of irrigating with various treated and untreated produced waters, including untreated coalbed natural gas (CBNG) produced water, untreated conventional oil and gas produced water, and produced water that had been treated using different treatment methods on crop biomass. The discoveries from this project are providing researchers with valuable insight into how crops are affected by produced water and helping them improve blending ratios for more effective irrigation.

- ***Geographic Information Systems (GIS)-based Tool to Improve Fluids Management*** – Colorado State University developed a GIS-based tool that reduces environmental impacts from drilling through improved environmental assessments of fluids management. The tool will help operators track air toxics and greenhouse gases associated with fluids handling, determine their water footprint, and place wells and treatment facilities in areas with less potential to impact the community.

- ***Water Desalination System Commercialized*** – Following a successful field demonstration project, Altela Inc., sold four AltelaRain modules that were installed at a water treatment facility in Williamsport, Pa., where they were treating almost 100,000 gallons of wastewater every day. In addition, Altela and its joint venture partners opened two new plants in 2012 for treating, recycling, and disposing of Marcellus shale wastewater located in Clarion and McKean Counties in western Pennsylvania.

- ***Advanced Water Filtration System*** – West Virginia University and its research partners developed an on-site multi-media filtration system to beneficially reuse produced water. After successfully testing the process in the laboratory, the team designed, fabricated and deployed a mobile treatment unit (MTU) to complete two field trials. Over 600,000 gallons of water were treated during field tests with 98.6 percent of the water recycled.

Lessons Learned

As with any type of research, produced water treatment and management research sometimes yields unexpected findings and uncovers challenges that need to be addressed through further research. The following high-level lessons learned have been identified.

- Re-use of produced water requires adequate environmental protections.
- Aside from DOE-funded research, industry developed and tested a myriad of water treatment technologies and systems as over the last 5 years.
- Preventing the fouling of heat exchangers and membranes is vital for certain water treatment processes to operate reliably.
- A primary constraint to re-using produced water for non-industry needs is the high cost of additional treatment to reach the required quality levels for those uses; however, technological advances are making this increasingly possible.
- Water management and re-use can be impeded by permitting delays and complex, unpredictable regulatory environments. The transportation and storage of brines brings added regulatory scrutiny; therefore, achievement of even partial removal of salts from produced water—a process called demineralization—can improve water handling flexibility.
- The challenges and the opportunities related to produced water and water management are often operator and regionally-specific and depend on both the physical and chemical properties of produced water from different formations and needs of the location where that water may be re-used. Thus, trying to develop a system or approach that has broad application is difficult.
- Industry and stakeholders are interested in increased transparency and data-sharing with regard to produced water and water management.

What are the benefits of produced water treatment and management?

The technology developed and demonstrated under this program is vital in addressing the environmental risks associated with unconventional oil and gas development. Along with this environmental stewardship, other benefits of this research are clear and include the following:

- **Conserving existing water supplies**. Developing effective fluid-management and beneficial reuse options reduces fluid-use associated with development. Reducing the demand for surface water resources by domestic and industrial users also protects wildlife and rivers.
- **Reducing costs.** Developing methods that allow producers to use resources more efficiently and fewer chemicals in the recovery and treatment process reduces the cost of environmental compliance. Successful R&D will also reduce costs associated with underground disposal of produced water.

  Significant hydrocarbon resources are found in the U.S.; resources that can be extracted and used to provide economic benefits for all Americans. New technologies to manage and treat the produced water from those resources are required in order to fully develop those unconventional oil and natural gas resources in an environmentally sustainable and safe manner. Engaging industry and academia to perform research catalyzes the development and application of these new technologies.
- **Stabilizing the domestic energy portfolio.** Ongoing and environmentally-sound development of domestic petroleum resources, specifically research that advances the development of unconventional resources, can help provide a more robust and stable domestic energy portfolio and economic benefits. A diverse portfolio of domestic energy sources will ultimately be a cornerstone in building greater energy independence and national security. Successful produced water treatment and management research will advance the development of unconventional fossil resources and mitigate or prevent the unwanted consequences of securing this energy supply.
- **Promoting technology transfer**. The technology developed and demonstrated under this program will be shared, scaled-up when applicable, and drive future discovery and exploration as it is applied by operators to future hydrocarbon resources.

Advancing a Web-based Tool for Unconventional Natural Gas Development with Focus on Flow back and Produced Water Characterization, Treatment and Beneficial Use

The Colorado School of Mines has developed a website for management of produced water. The site features a selection tool for determining the most appropriate technology for treating water given the water quality as well as regulatory and other information.

Additional details about this project are available on p. 22.

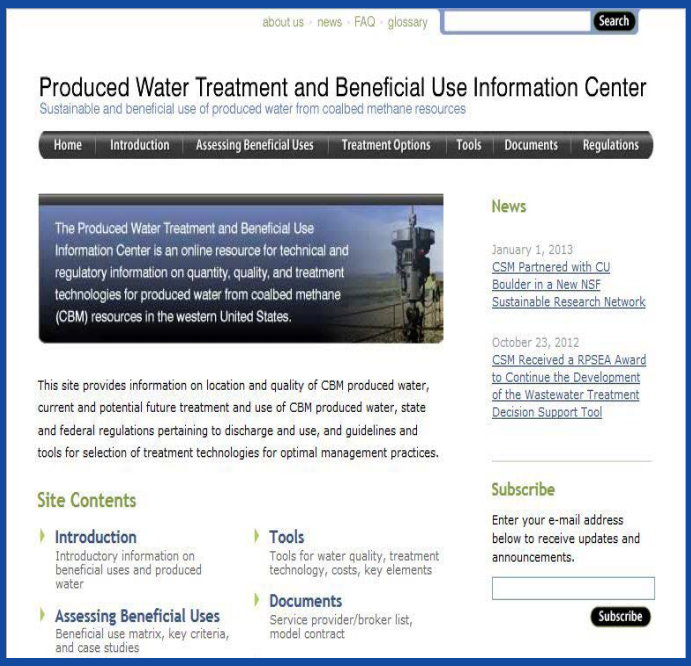


Image caption: **This project produced a website that helps industry manage produced water.**

Matrix of Produced Water Management and Treatment Projects

Bin sub-area / project	Lead performer	Report page no.
PRODUCED WATER TREATMENT/MANAGEMENT		
07122-12: An Integrated Framework for the Treatment and Management of Produced Water	Colorado School of Mines	14
08122-05: Barnett and Appalachian Shale Water Management and Reuse Technologies	Gas Technology Institute	16
08122-36: Pretreatment and Water Management for Frac Water Reuse and Salt Production	GE Global Research	18
10122-07: NORM Mitigation and Clean Water Recovery from Marcellus Frac Water	GE Global Research	19
10122-39: Novel Engineered Osmosis Technology: A Comprehensive Approach to the Treatment and Reuse of Produced Water and Drilling Wastewater	Colorado School of Mines	20
11122-31: Development of Plasma Technology for Water Management of Frac/Produced Water	Drexel University	21
11122-53: Advancing a Web-based Tool for Unconventional Natural Gas Development with Focus on Flowback and Produced Water Characterization, Treatment and Beneficial Use	Colorado School of Mines	22
11122-55: Development of GIS-Based Tool to Optimize Fluids Management in the Shale Gas Industry	Colorado State University	23
11122-56: Understanding and Managing Environmental Roadblocks to Shale Gas Development: An Analysis of Shallow Gas, NORMs, and Trace Metals	University of Texas at Austin, Bureau of Economic Geology	24
11122-57: Advanced Treatment of Shale Gas Frac Water to Produce NPDES (National Pollution Discharge Elimination System) Quality Water	Southern Research Institute	25
11122-60: Cost-Effective Treatment of Flowback and Produced Waters via an Integrated Precipitative Supercritical (IPSC) Process	Ohio University	26
11122-71: Water Handling and Enhanced Productivity from Gas Shales	University of Southern California	27

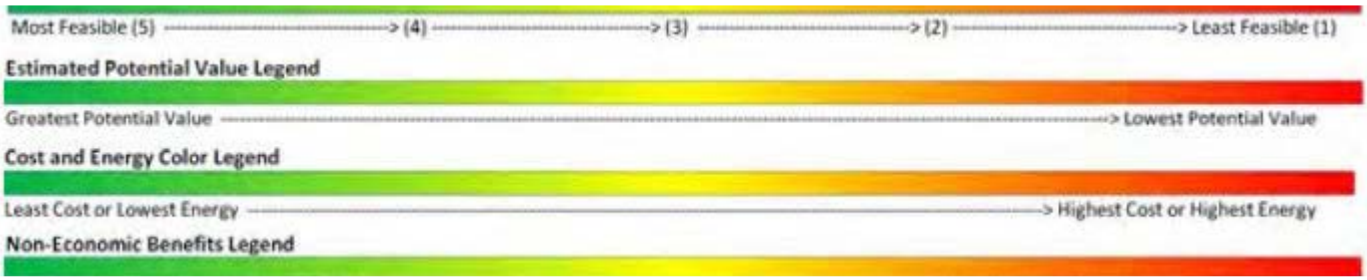
An Integrated Framework for the Treatment and Management of Produced Water—Colorado School of Mines; 9/2008-6/2011

Objective: The increasing water demands associated with energy production stress the western United States, an area already lacking adequate water resources. Exacerbating 0this problem is the fact that the majority of U.S. population growth is projected to occur in western states through the year 2020. Nevertheless, approximately 430 million gallons of produced water are generated each day within just the five Rocky Mountain States included in this project (Colorado, Montana, New Mexico, Utah, and Wyoming). The cost of managing produced water is a significant factor in the profitability of a well. If the cost exceeds the value of the oil or gas produced, well operations are usually shut down. Although treatment, management, and reuse options exist, they are not the same for every well and vary depending on the physical and chemical properties of the produced water. Those properties depend on the geographic location and formation of the field from which the produced water comes.

With effective treatment and management, produced water can have many possible beneficial potable and non-potable re-uses, including aquifer recharge storage and recovery, surface water discharge, irrigation, and wildlife maintenance and enhancement. The objective of this project was to develop an integrated guidance framework that links the composition of produced waters from coalbed methane (CBM) and gas shale operations to their beneficial uses.

Research Conducted: The project team brought together gas producers, members of the water treatment industry, regulatory agencies, tribal interests, landowners, agricultural stakeholders, and environmental groups. Together, they identified solutions to institutional obstacles limiting the beneficial use of treated water. Researchers collaborated with these stakeholders to develop a water quality database for individual basins, augmented by water quality information in the public domain and information from industry partners operating in those basins. The project team then compiled a comprehensive database of current treatments for produced or brackish water, and of emerging technologies for desalination. Each treatment process was ranked following development of assessment criteria. Novel and emerging pre-treatment technologies, such as ceramic ultrafiltration membranes, were explored along with well-developed pre-treatment processes including chemical flocculation and media filtration, cartridge filtration, microfiltration, and ultrafiltration. Researchers incorporated cost-benefit analyses that considered technical and non-technical factors in order to link the composition of produced water to beneficial use applications and identify the best strategies for management and treatment of produced water depending on field conditions. The team considered both established and emerging desalination technologies and identified potential treatment process combinations for minimizing the volume of residual concentrated brines.

Accomplishments: The project team developed the *Produced Water Treatment Beneficial Use Screening Tool*. The tool is a macro-enabled Excel workbook that contains four modules: Water Quality Module, Treatment Selection Module, Beneficial Use Screening Module, and Beneficial Use Economic Module. Together, they provide an integrated decision framework to assess produced water options. The guidance framework considers the field conditions where the water was produced to identify the most useful, cost-efficient, and environmentally sound strat-



The table at the top of the Screening Matrix worksheet provides a color coded and quantified assessment of the feasibility and relative complexity.

An Integrated Framework for the Treatment and Management of Produced Water—Colorado School of Mines; 9/2008-6/2011

egies for managing and treating it.

Benefits: The techniques and methods developed by project researchers provide industry guidance for selecting the most cost-efficient management and treatment strategies for handling produced water under site-specific conditions during CBM and gas shale operations. These techniques, along with cost-benefit analyses and life-cycle analyses, will help researchers develop strategies to manage and dispose of brine streams, explore and develop existing and emerging desalination technologies, and highlight beneficial use scenarios. By focusing on beneficial-use opportunities of produced water, the industry will be better able to plan for its management and treatment, which may reduce costs, minimize potential environmental impacts, and enhance the gas recovery, longevity, and economic viability of CBM and gas shale fields.

Ongoing Activity and Future Plans: Colorado School of Mines received a new RPSEA award (Project Number 11122-53 – see page 22) to continue the development of the wastewater treatment decision support tool and its related website. The tool will be expanded to include treatment of waste streams from other unconventional oil and gas sources.

Lessons Learned: To determine which treatment process is necessary once the quality of produced water is known, users of the tool required a matrix that details water quality criteria for various beneficial uses. Underground injection in class II wells and evaporation ponds are not included in the matrix, as both methods are considered disposal options rather than beneficial use of produced water.

Key Contact: Jorg Drewes, Colorado School of Mines, 303-273-3421, jdrewes@mines.edu

Project Number: 07122-12

The final report for this project is available at: http://www.rpsea.org/media/files/project/33f1410a/07122-12-FR-Integrated_Framework_Produced_Water-06-30-11_P.pdf.

Barnett and Appalachian Shale Water Management and Reuse Technologies—Gas Technology Institute; 8/2009-3/2012

Objective: Approximately 1 million gallons of water are used when fracturing vertical wells, while horizontal wells require 3 to 4 million gallons for successful completion. More than 90 percent of the wells constructed in both the Barnett and Marcellus shale plays are horizontal wells, and the required volumes of water for well completion present management and reuse challenges for the industry. This project was initiated to characterize the chemical nature of flow back water, provide environmentally acceptable options for flow back water management, evaluate water reuse approaches to reduce freshwater demand, and assist with developing sustainable water management plans in the Barnett and Appalachian shale plays.

Research Conducted: The project team worked with large industry consortiums, the Pennsylvania EPA, U.S. EPA, and others to conduct research and analyses and develop and test technologies. Researchers examined the composition of produced waters from 19 sites in the Marcellus region in Pennsylvania and West Virginia and 11 early-production sites in the Barnett region in northern Texas. They focused on the brine streams generated during the fracturing flow back process to create a database from two distinct geographical locations that includes flow back rates and volumes of the injected water and the recovered produced water. The database also includes chemical analyses comprising information usually found in drinking water analyses, plus that of 70 volatile organics, 116 semi-volatile organics, 22 pesticides, PCBs, and 27 metals. Notably, the data trends indicate that heavy metal contamination is minimal. Most of the recovered organic matter consists of typical wastewater components with established and effective treatments. However, high concentrations of divalent cations were discovered. Separation and treatment options for those salts, including electrodialysis (ED) methods for desalinating shale gas waters for reuse, were investigated. Additionally data were collected over a 60-day period from a processing plant that uses an advanced thermal mechanical vapor recompression process to treat produced water in the Barnett shale region. Novel approaches for locating and evaluating significant sources of water that do not compete with community water supply demands in the Barnett Region were also explored.

Accomplishments: Through the application of innovative coatings on the surfaces of ultrafiltration and reverse osmosis membranes, and through technology transfer that allowed this technology to be applied commercially, the project team was able to double membrane life while reducing the energy demands of produced water treatment by more than 35 percent. Research into ED flow back water demineralization led to design improvements that resulted in a 65 percent reduction in the chemical inputs and 40 percent reduction in the required energy demands over conventional ED processing. Scientists also confirmed the successful operation of a high-efficiency mechanical vapor recompression conversion of flow back and produced waters under actual field conditions. Other accomplishments include the development of an information base of integrated flow back water characteristics for the Barnett and Marcellus shale plays, a GIS framework, and protocols for locating and estimating significant alternate water sources.

Flash mixer and clarifier.

Benefits: Knowledge of expected water conditions will result in better engineering and implementation of water treatment technologies, including industrial membranes. Improvements in industrial membranes not only lead to more efficient processing of produced water, but to lower capital and operating costs. Recycling produced water project also:

- Reduces industry demand of freshwater for shale gas developments.

Barnett and Appalachian Shale Water Management and Reuse Technologies—Gas Technology Institute; 8/2009-3/2012

- Eases water availability constraints to well development and completion.
- Decreases environmental impacts due to water transportation. These include air impacts, fugitive dust, traffic, and carbon footprint.
- Technologies and know-how can be extended to the development of other shale gas basins.

Ongoing Activity and Future Plans: This project is complete, and no further activities are planned.

Lessons Learned: ED research highlighted the need for a multivalent cation exclusionary membrane to protect the cathode barrier membrane from high calcium concentrations; without the protection, energy costs could be reduced as much as 40 percent. Additionally, low-cost clean-in-place technology is necessary to keep the ED unit operational. The rate of the process can be improved by at least 15 percent by using waste heat to increase the temperature of the electrolyte, the water, or both.

Researchers also learned that, in most cases involving dense development of a gas resource, sufficient water is theoretically available to meet the demand of shale gas development. Practically, however, more than half of the total available water is on the surface and thus susceptible to evaporation during droughts. The alternative water sources identified in this study may not be economically viable alternatives, as they are fragmented among many small water bodies, low yield wells, and wastewater streams.

Key Contact: Thomas Hayes, Gas Technology Institute, 847-768-0722, tom.hayes@gastechnology.org

Project Number: 08122-05

The final report for this project is available at: http://www.rpsea.org/files/4129/.

Pretreatment and Water Management for Frac Water Reuse and Salt Production—GE Global Research; 8/2009-9/2011

Objective: Hydrofracturing flow back and produced water (collectively referred to as "frac water" here) have historically been driven off-site for disposal by deep-well injection in salt formations or delivery to wastewater treatment plants; however, the capacity of injection sites near many shale gas plays is severely limited and regulatory changes are restricting delivery to treatment plants. For example, as of 2011, shale gas drillers could no longer deliver wastewater to Pennsylvania's 15 treatment plants that had been accepting it. Additionally, water is trucked to fracking sites at plays where available water is limited. Thus, cost-effective methods for recovering and reusing frac water are necessary for sustained development of shale gas plays. Because most frac flow back occurs within the first month of hydraulic fracturing, ideally those methods would allow mobile operation. The overall objective of this project is to develop an economic process to treat frac water by developing a wastewater pretreatment process, primarily for barium and radium removal. The process will allow the recovery of distilled water and a salable salt product from Marcellus shale gas produce water high in total dissolved solids (TDS). Results of this project will identify cost, performance, and adaptability to mobile operation for each pretreatment technology investigated.

Research Conducted: As softened frac water allows for a higher recovery of both distilled water and salt product with a smaller waste stream, this project focused pretreatment methods on removing hardness and other multivalent cations from high-TDS brines. In this case, it involved removal of radium (a naturally occurring radioactive material [NORM]) and barium. Based on a pilot study conducted by GE Water and Process Technologies, the project team defined three types of produced water based on the water's barium and radium concentrations, with three different pretreatment needs. Type I requires no pretreatment prior to sodium chloride (NaCl) crystallization. Type II produced water, with greater than $[Ba]_{max}$ and very low radium activity, can be treated with the established economical method of sulfate precipitation before NaCl crystallization. Type III produced water must be softened, as it has a barium concentration greater than $[Ba]_{max}$ and higher radium activity.

Researchers obtained three samples of frac water from Marcellus shale gas wells in Pennsylvania and analyzed them for naturally NORM by multiple methods. They calculated the required volumes of regeneration chemicals and rinse water before ruling out ion exchange as a softening method for the frac water. They also developed a modified lime-soda softening process that softens the Type III water completely. In this process, magnesium, calcium, and strontium were selectively precipitated to yield a solid sludge that may be disposed of as nonhazardous waste in certain facilities. Following that, barium and radium were precipitated as carbonates, and then dissolved into a liquid that can be disposed of by underground injection control (UIC). In a second process, the produced water was softened by removing barium and radium by adsorption onto a MnO_2 adsorbent.

Accomplishments: A scintillation counting method was developed for this project to measure the reduction of NORM levels in frac water after pretreatment. The research team also developed models for the chemical treatment of frac water, calculated material balances for lime softening and sulfate precipitation, and simulated a thermal brine concentrator and crystallizer with lab apparatus for thermal water and NaCl recovery.

Benefits: Cost-effective recovery and reuse of produce water is vital to continued shale gas production and will greatly reduce the net consumption of fresh water required for well development and operation. Additionally, if the practice of re-injecting produced water into disposal wells is eliminated, then potential contamination of the water supply may be avoided.

Ongoing Activity and Future Plans: This project is complete, and no further activities are planned.

Lessons Learned: Researchers initially noted that the NORM levels in the brines they were testing were about three to five times normal. However, they evaluated their data and discovered a problem with the scintillation counting technique they were using for measuring NORM in frac water samples. After testing alternate scintillation cocktails, the team developed a new technique and resolved the problem.

Key Contact: James M. Silva, General Electric Global Research

Project Number: 08122-36

The final report for this project is available at: http://www.rpsea.org/media/files/project/18621900/08122-36-FR-Pretreatment_Water_Mgt_Frac_Water_Reuse_Salt-01-26-12.pdf.

Naturally-Occurring Radioactive Materials (NORM) Mitigation and Clean Water Recovery from Marcellus Frac Water—GE Global Research; 08/2009-09/2011

Objective: Water management is a key challenge to fully developing the Marcellus shale gas play. Cost-effective disposal options for produced water are limited in Pennsylvania, and the composition of produced water from much of the Marcellus compounds the issue. Much of the frac water from the area contains high levels of naturally occurring radioactive materials (NORM), primarily radium and barium. Although approximately 83 percent of the produced water from Marcellus unconventional shale gas wells was reused for fracturing in 2012, processes are needed for recovering produced water as clean water for beneficial uses or safe discharge. The focus of this project was on developing a hydraulic fracturing wastewater pretreatment process to remove naturally occurring radioactive material (NORM) from a wastewater stream for subsequent treatment in an economical membrane distillation system. The objective of this study was to define and validate pretreatment processes for Marcellus shale gas produced water to facilitate cost-effective water and salt recovery, and to develop a brine concentrator based on membrane distillation (MD) suitable for Marcellus frac water desalination.

Research Conducted: Researchers developed the Aspen Plus™/OLI Systems model for the evaporation and crystallization processes, and then validated the model in the laboratory. The model agreed with the temperature profile and the concentration factor required for salt crystallization. The project team used the model and experimental results to define water and salt recoveries for produced water from Marcellus wells and expanded the models to include pretreatment, evaporation, crystallization, and salt crystal treatment. They validated their sulfate pretreatment process at both lab- and pilot- scale. The project team then developed and tested a design case produced water composition based on a 2011 survey of one Barnett and six Marcellus produced waters. Additional samples were taken across a broad region spanning Green County in southwest Pennsylvania to Bradford County in northeast Pennsylvania. The compositions of both sample sets were characterized. To develop a membrane distillation process driven by mechanical vapor compression (MVC-MD), the team developed thermodynamic models of the system, which agreed with the bench and field test results. Clean-in-place processes consisting of rinses with fresh water and solutions of hydrochloric acid and sodium hydroxide were also tested for 7 and 24 hours.

Accomplishments: The pretreatment system developed as part of this project resulted in salt crystals with NORM activity low enough for the recovered crystals to be beneficially reused in Pennsylvania or disposed of at a nonhazardous solid waste landfill without further treatment. With membrane models, researchers showed that although permeability decreases with increasing system temperature, the energy consumed by MVC-MD actually decreases. Thus, because salt increases the boiling temperature of aqueous solutions, it lowers the vapor pressure. The project team also found that the study supported the use of MVC-MD technology to treat the high total dissolved solids brines produced from shale gas wells.

Benefits: Cost-effective recovery and reuse of produce water is vital to continued shale gas production and will greatly reduce the net consumption of fresh water required for well development and operation. Additionally, if the practice of re-injecting produced water into disposal wells is eliminated, truck traffic, noise, and dust pollution could be significantly reduced and the risk of potentially contamination of the water supply is reduced. While direct frac water reuse is an effective method for frac water disposal, frac water recovery to generate clean water and a salable salt product is essential to long-term shale gas development.

Ongoing Activity and Future Plans: This project is complete, and no further activities are planned.

Lessons Learned: The membrane leaked salt water twice during membrane field testing. The issue was resolved in each case by rinsing the membrane in clean tap water. Leakage was negligible during the longer subsequent test, a result attributed to maintaining a higher feed flow rate per membrane area.

Key Contact: James M. Silva, General Electric Global Research

Project Number: 10122-07

The final report for this project is available at: http://www.rpsea.org/files/3732/

Novel Engineered Osmosis Technology: A Comprehensive Approach to the Treatment and Reuse of Produced Water and Drilling Wastewater—Colorado School of Mines; 6/2012-6/2015

Objective: The objective of this project is to investigate osmotically-driven membrane processes for use in the treatment and recovery of produced water for beneficial reuse. These processes use osmosis to drive the extraction of clean water from complex and impaired liquid streams, while concentrating and minimizing the volume of the contaminated streams. This research will advance the development and implementation of forward osmosis (FO) and osmotic dilution, while proving novel ultrafiltration processes for the treatment and management of drilling and flow back water in unconventional and conventional gas and oil fields.

Research Conducted: To investigate the changes in membrane manufacturing process parameters and membrane polymers necessary for better performance in fouling and scaling environments, the project team and Hydration Technology Innovations (HTI), an industry partner, worked to enhance two of HTI's existing membranes. Researchers modified the surface chemistry of a cellulose triacetate (CTA) membrane to enhance flux, and investigated thin film composite (TFC) polyamide FO membranes. They discovered that the CTA membrane is less likely to foul than the TFC membrane. The team then investigated the effects of different operating conditions on the membranes' performance. Novel ultra-filtration (UF) membranes were also prepared from chemically modified polymers of flat sheet FO membranes to create different pore size and molecular weight cutoffs. Results indicated that the new UF membranes do not offer an advantage over commercial FO membranes. Analytical techniques were used to comprehensively characterize the membranes. Capillary FO membranes were also developed and tested under simulated conditions with synthetic feed water, and under realistic conditions using produced water. The results of these studies were promising.

Accomplishments: The project team discovered that the modified CTA membranes are less likely to foul than the TFC membranes. As a whole, the results of the modified-CTA membrane work have convinced the team that the novel membrane will be a primary focus for upcoming pilot testing. The team is also developing a computer program for simulation and modeling of osmosis systems. HTI data are being used to fine tune and validate the early models, but initial simulations have been successful.

Benefits: Some regions are at high risk for water depletion and would benefit from beneficial reuse of waste streams. This research may provide a viable option for large-scale produced water reuse, drastically reducing industrial water demands, promoting closed loop water recycling and minimizing the environmental impacts associated with gas and oil production.

Ongoing Activity and Future Plans: This project is complete, and no further activities are planned.

Lessons Learned: The team originally planned to study membrane-fouling results and perform analytical analyses of the UF membranes derived from FO membranes. However, results demonstrated that these novel membranes do not offer advantages over commercially available UF membranes, so the focus has was shifted to commercial FO membranes for pretreatment studies.

In scale demonstrations, the researchers saw the FO systems produce a net cost advantage of between 45 and 60 percent compared to traditional disposal methods.

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Project Number: 10122-39

More information about this project can be found at: http://www.rpsea.org/projects/10122-39/

Development of Plasma Technology for Water Management of Frac/Produced Water—Drexel University; 4/2013-4/2015

Objective: The goal of this project is to develop an integrated plasma water treatment system to enhance the management of flow back or produced water created during hydraulic fracturing operations. To accomplish this, three key processes will be integrated into the system: a novel water softening technology utilizing plasma arc discharge, a plasma-assisted self-cleaning filter, and an integrated plasma unit with vapor-compression distillation for produced water treatment.

Research Conducted: The project team demonstrated, in a laboratory setting, the validity of a plasma-induced softening process to pretreat produced water. The process involves two circular electrodes. The top electrode acts as the cathode, while the bottom serves as an anode, with a gliding arc generated between. Compressed air moves the arc in a circle between the two electrodes. In this manner, a plasma arc jet is formed in (and makes direct contact with) the produced water. The project team has designed and constructed a flow filtration system using a 0.2 micron membrane filter to demonstrate the validity of plasma-assisted self-cleaning filtration with produced water. The study will determine whether the 0.2-micron filter is sufficient to filter the produced water.

Accomplishments: Project scientists created both gliding arc discharge and pulsed spark plasma discharges in produced water. The new 600W gliding arc discharge (GAD) successfully reduced the bicarbonate concentration of produced water from 830ppm to 420ppm at a flow rate through the GAD reactor of 0.1 L/min. The gliding arc plasma discharge also demonstrated antibacterial properties during laboratory tests, reducing sulfate-reducing bacteria and acid-producing bacteria levels in produced water. The team also suggests that this method might reduce or inhibit microbiologically influenced corrosion in the field.

Benefits: Traditional strategies for preventing the formation of scale on field equipment often rely on reverse osmosis, ion exchange, or the addition of soda ash to reduce the calcium content of fluids. The concentration of calcium ions in produced water is often too high for those options to be practical, so industry instead removes bicarbonate ions to soften the water. This is accomplished by adding lime, which has the unwanted side effect of increasing the overall mass of solids. Disposal of those solids increases costs. Using a plasma discharge to target bicarbonate in produced water disassociates the calcium and bicarbonate ions in water, thus softening the fluid without adding other solid materials.

Ongoing Activity and Future Plans: A demonstration of the plasma assisted self-cleaning filter is in progress. Investigators also will design, construct, and test the vapor-compression distillation unit. With the plasma discharge unit available to pre-treat produced water, the team believes the distillation unit can be operated without the presence of calcium fouling the unit.

A patent "Pre-treating water with non-thermal plasma" (US 20140124357) was recently awarded for the technology.

Lessons Learned: The first part of this study used produced water samples from a Marcellus shale gas well; however, municipal or distilled water with bicarbonate and calcium artificially added was used to verify that bicarbonate removal would prevent scale removal. Researchers predicted that using produced water for the fouling component of the study would result in oversaturation of NaCl, which could interfere with quantification of scale formation.

The project team discovered that different plasma treatment times were required to completely remove bicarbonate from produced water. These results were unexpected and additional research is necessary to investigate the causes.

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Project Number: 11122-31

More information about this active project can be found at: http://www.rpsea.org/projects/11122-31/

Advancing a Web-based Tool for Unconventional Natural Gas Development with Focus on Flowback and Produced Water Characterization, Treatment and Beneficial Use—Colorado School of Mines; 5/2013-6/2016

Objective: The objective of this project is to provide web-based tools for producers and others who need to characterize, treat, and beneficially use and manage flow back and produced water from unconventional wells. This work is an expansion of a previous RPSEA-sponsored project that developed an integrated framework for treatment and management of coalbed methane produced water.

Research Conducted: This project is still new; however, under the scope of the previous RPSEA-funded project, the team developed the Produced Water Treatment Beneficial Use Screening Tool. The tool is a macro-enabled Excel workbook that contains four modules: Water Quality Module, Treatment Selection Module, Beneficial Use Screening Module, and Beneficial Use Economic Module. Together, they provide an integrated decision framework to assess produced water options. The guidance framework considers the field conditions under which the water was produced and identifies the most useful, cost-efficient, and environmentally sound strategies for managing and treating the water.

Benefits: This project will help minimize the potential impacts of gas production on natural water resources, public health, life, and the environment. It will also provide industry and decision makers with techniques and methods to address challenges associated with developing technically sound and environmentally friendly water management strategies for unconventional gas exploration and production.

Ongoing Activity and Future Plans: Researchers will develop a comprehensive database of the qualities and quantities of waters associated with shale gas and tight sand plays in the major producing basins within the U.S. They will perform a broad assessment of current and emerging technologies used to manage and treat produced and flow back waters. Beneficial reuse technologies will be included in that assessment.

The project team will gain a better understanding of the chemical composition of produced waters and will investigate the impact of that composition on the environment and public health. Additionally, the current integrated framework for coalbed methane produced water management will be added and more functional macro-enabled Excel workbook modules will be made available. Those modules will be expanded to include treatment and beneficial use options for flow back and produced waters and will evaluate the feasibility, costs, and benefits of different reuse scenarios. The modules will also enable users to assess water quality, select appropriate treatment trains, and view industry-supported case studies to illustrate and validate the application of the tools. Information about institutional, regulatory, legal, and other challenges associated with flow back and produced waters also will be included.

Lessons Learned: This project has not concluded yet. Lessons learned will be included in final report upon project conclusion.

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Project Number: 11122-53

More information about this project can be found at: http://www.rpsea.org/projects/11122-53/.

Development of GIS-Based Tool to Optimize Fluids Management in the Shale Gas Industry—Colorado State University; 3/2013–3/2015

Objective: The objective of this study is to develop a GIS-based tool to enable producers and other users to optimize the management of fluids from unconventional gas production. The goal is to sustain gas production while minimizing potential impacts on natural water resources, public health, and the environment. The study, based on the integrated decision making framework developed for coalbed methane produced water management, is designed to focus on shale gas and tight sand production and will extend over 36 months.

Research Conducted: The research is organized into four phases, as shown in the image. The overarching objective is to develop GIS-based tools for use in making water management decisions during unconventional oil and gas development. The tool will assess handling, treatment, and disposal of produced water, air toxins, and greenhouse gases associated with fluids handling, water footprint, and the optimal siting of wells and treatment facilities in order to minimize community impacts. Protocols for predicting water production have been developed based on both temporal and spatial variations of water quantity. The team used dissolution kinetics and geospatial data to propose a water quality prediction framework. A case study has been performed on Noble Energy wells in Yuma County, Colorado using both water quantity and quality protocols.

Accomplishments: Three different protocols have been created to estimate and predict produced water quantity and quality from shale gas wells.

The case study in Yuma County demonstrated that by altering decline models and coefficients, the prediction methods developed by the project team can be used in other shale gas fields.

Benefits: The benefits of this project include minimizing the potential effects of gas production on natural water resources, public health, life, and the environment.

Fluids management is vital to ensuring the protection of the environment during the petroleum resource development. The GIS-based tool will help minimize community impacts such as truck traffic, noise and road damage, and air quality issues. It will assist with well pad siting and density decisions and may result in a smaller regional water footprint.

Ongoing Activity and Future Plans: The team will investigate the chemical composition of produced waters. The current integrated framework for coalbed methane produced water management will be added to the GIS tools, with more functional and expanded macro-enabled Excel workbook modules becoming available. The modules will enable users to assess water quality, select appropriate treatment trains, and view industry-supported case studies to illustrate and validate the application of the tools. Information about institutional, regulatory, legal, and other challenges associated with flow back and produced waters will also be included.

Lessons Learned: This project has not concluded yet. Lessons learned will be included in final report upon project conclusion.

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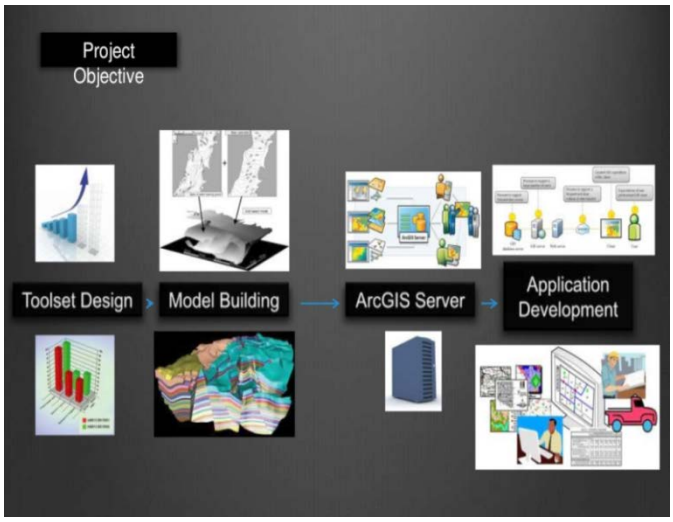
Project Number: 11122-55

More information about this project can be found at: http://www.rpsea.org/projects/11122-55/



Understanding and Managing Environmental Roadblocks to Shale Gas Development: An Analysis of Shallow Gas, NORMs, and Trace Metals—University of Texas at Austin, Bureau of Economic Geology; 6/2013–6/2015

Objective: Researchers seek to understand the natural system's geochemistry and its behavior when perturbed by hydraulic fracturing. The objectives of this project are to:

1. evaluate sources and mobilization mechanisms for shallow gases in aquifers using chemistry, isotopes, microbes, and noble gases;
2. assess quantity and mobilization mechanisms of trace metals and NORMs using laboratory batch experiments with injected water (fresh to brackish) and produced water to determine the impact of water chemistry on mobilization of trace metals and NORMs; and
3. develop best management practices with respect to characterizing sources and processes impacting shallow gas in aquifers.

Research Conducted: The project team has collected over 200 water samples for dissolved gas analysis and located several methane hotspots. Autoclave experiments on Barnett and Haynesville shale samples have also begun.

Benefits: Operators have been conducting field experiments since the production of unconventional resources began. However, science and scientific understanding lags behind. The laboratory component of this study will fill some of those gaps and add to the body of knowledge relating to the nature of produced water and downhole rock-water interactions. Some benefits related to the field component of the study include the documentation of natural methane contamination of groundwater in Texas, and an understanding of the processes that lead to methane accumulation in the shallow subsurface. With this knowledge, mediation of groundwater contamination can be planned and technology can be developed to provide greater environmental protection.

Ongoing Activity and Future Plans: Shallow gas will be documented through extensive sampling for dissolved gases (components, concentrations, and isotopic composition) of aquifers in Texas's hydrocarbon-producing shale and tight formations. Sampling will be followed by a detailed analysis of some hotspots, considering industry activities as well as structural analysis, noble gas studies, and hydrogeological and microbial investigations. To achieve the second objective, controlled autoclave experiments will be performed while exposing shale fragments to various fluids. Reacted and unreacted rocks will be examined and the chemical composition of the evolving fluids will be documented over time.

Lessons Learned: This project has not concluded yet. Lessons learned will be included in final report upon project conclusion.

Key Contact: Jean Nicot, University of Texas at Austin

Project Number: 11122-56

This is an active project; therefore, the final report is not available yet. A project summary can be accessed at: http://www.rpsea.org/media/files/project/e1f651b6/11122-56-PFS-Environmental_Roadblocks_Shale_Gas_Development_Analysis_NORMs_Trace_Metals-03-03-14.pdf

Advanced Treatment of Shale Gas Frac Water to Produce NPDES (National Pollution Discharge Elimination System) Quality Water—Southern Research Institute; 4/2013–4/2015

Objective: Novel, cost effective, and environmentally sound methods for managing and treating wastewaters and residues from hydraulic fracturing operations must be developed for producers to continue shale gas development. The goal of this project is to evaluate an integrated approach to hydraulic fracturing water treatment, using magnetic ballast clarification (MBC) for removing total suspended solids, metals, and naturally occurring radioactive materials (NORMS); vortex-generating and nano-filtration membranes to remove total suspended solids and total dissolved solids; and hydrogel adsorbent for metals, NORMs, and trace element removal or precipitation, solidification and stabilization technologies. Ultimately, researchers hope to achieve the following goals:

1. Produce water suitable for national pollutant discharge elimination system (NPDES) discharge and/or beneficial reuse pursuant to state regulations
2. Produce a brine slurry with metal concentrations below detection limits
3. Volumetrically decrease the metals waste to be disposed of and solidify/stabilize solid wastes for subsequent disposal.

Research Conducted: In order to develop advanced technologies for handling and disposal of large volumes of produced water, researchers will optimize four technologies: two for hydraulic fracturing water treatment and two for the treatment and disposal of residues with high solid slurry and membrane concentrate from hydraulic fracturing water treatment.

The technologies include magnetic ballast clarification for the removal of total suspended solids (TSS), metals, naturally occurring radioactive materials (NORMS); and vortex-generating and nano-filtration membranes designed to remove TSS and total dissolved solids. The technologies to be investigated for residue treatment and disposal technologies are hydrogel adsorbent to mediate metals, NORMs, trace element removal, and to precipitate, solidify, and stabilize those fouling components. Researchers will also evaluate several combinations of these technologies.

Accomplishments: Early research reports indicate the proposed technologies are very efficient in managing low-salinity flow back waters. Additionally, using the MBC and FMX techniques, greater than 98 percent of TSS and 95 percent of iron was produced water samples. After disinfection, the treated water is suitable for reuse in fracking operations. Thus far, NPDES-quality water can be achieved for produced and flow back waters with < 60,000 mg/L TDS.

Benefits: Benefits from this project include the development of a novel produced water management and treatment technology. If successful, this new method will provide a less expensive approach for treating produced water, enhancing the economic viability for producers and providing fracking operators with the ability to reduce negative environmental impacts at local levels.

Ongoing Activity and Future Plans: The team will conduct a series of bench-scale simulations to develop a method to evaluate whether waters from specific wells can be treated with MBC, membranes, hydrogel media, or by precipitation, solidification, or stabilization. Upcoming research includes:

- Conducting column studies for metals and NORMs removal using membrane concentrates
- Conducting Solidification and stabilization studies
- Process integration and optimization
- Field pilot work

Lessons Learned: This project has not concluded yet. Lessons learned will be included in final report upon project conclusion.

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Project Number: 11122-57

This is an active project and the final report is not yet available. However, more information about the project can found at: http://www.rpsea.org/projects/11122-57/

Cost-Effective Treatment of Flowback and Produced Waters via an Integrated Precipitative Supercritical (IPSC) Process—Ohio University; 6/2013–6/2015

Objective: The objective of this project is to develop and validate the integrated precipitative supercritical (IPSC) process for converting wastewater from unconventional shale gas wells into a clean water product for discharge or reuse.

Research Conducted: Produced water from hydraulically fractured wells can be treated for reuse by separating impurities using a combination of chemical and mechanical separation methods. The IPSC process is based on that premise; produced water is treated using one or more hydrocyclone particulate filter, an ultra-violet treatment unit, a sulfonation unit, a softening unit, a hydrolysis unit to remove targeted dissolved solids, and a radioactive material adsorption unit. Once the produced water is treated, it is introduced into a super critical reactor and is heated to super critical temperatures, causing the water to behave as non-polar and the remaining dissolved solids precipitate. The precipitated salts are collected at the bottom of the unit and purified water exits through the top of the unit.

Accomplishments: This project has not yet reported accomplishments.

Benefits: Successful demonstration of this project will provide a cost-effective produced water treatment process that can be used at well sites, providing a supply of clean water for beneficial reuse and eliminating the need to transport water offsite. In addition, during treatment, any hydrocarbons present in the produced water decompose and undergoes a water/gas shift reaction to form hydrogen and carbon dioxide. This gas mixture can be used with well head gas to power super critical reactor.

Ongoing Activity and Future Plans: During the first phase of the project, the team will complete bench-scale testing of UV treatment, chemical precipitation/adsorption, and supercritical water testing to validate the technologies. Researchers will also acquire knowledge to prepare for designing, constructing, and operating a pilot-scale IPSC process unit. In the second phase, the team will construct and operate a fully integrated pilot-scale prototype process unit able to treat a barrel of flow back water per day[1]. This demonstration will help the team acquire the necessary engineering information to develop a detailed techno-economic evaluation and a commercial-scale engineering design package.

1 http://www.ohio.edu/compass/stories/12-13/11/is-ee-grant-2012.cfm

Lessons Learned: This project has not concluded. Lessons learned will be included in final report upon project conclusion.

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Project Number: 11122-60

This is an active project; therefore, the final report is not available yet. However, more information about this project can be found at: http://www.rpsea.org/projects/11122-60/

Water Handling and Enhanced Productivity from Gas Shales—University of Southern California; 8/2013–8/2015

Objective: Researchers will utilize a combination of computer modeling, field tests, and laboratory experiments to characterize Marcellus Shale core samples and gain a better understanding of the interactions between the shale matrix and fracturing fluids used to stimulate production wells. With a better understanding of the influence those interactions may have on well productivity, researchers will provide new guidelines and presenting optimal choices for the treatment and reuse of flow back water. Another focus is on the beneficial reuse of produced water through the application of various pre-treatment options.

Research Conducted: A collection of Marcellus core samples from southwest and central Pennsylvania, provided by ECA, is being used for the lab-scale work. The experimental program focuses on the exposing a shale fracture face to frac-fluids, then observing mass-transfer characteristics and shale-fluid interactions. Mixtures of fresh and produced water, as well as produced water that has undergone treatment, will be used. Geochemical analysis of shale and produced water samples will be done, allowing for the development of guidelines for optimal mixing of fresh and produced water. Invasion characteristics of fluid mixtures into the micro fractures and the shale matrix will also be evaluated. The observed fracture networks and geochemical reactions will be modeled to elucidate any long-term impact on gas production rates.

Accomplishments: To-date, the researchers have developed a shale gas simulator SUNGAS and used it to conduct sensitivity analysis; added the simulation of gaseous tracer to the simulator; conducted the sensitivity analysis of the Klinkenberg effect and investigated the effects of pressure and permeability on the Klinkenberg factor; extended SUNGAS to a fully coupled hydrological-mechanical simulation parallel version called SUNGAS-HM-MP; improved the mean stress simulation module of SUNGAS-HM-MP to the simulation of all three principal stresses; and conducted simulation on cores using the tracer.

Benefits: An understanding of how fluid and shale interactions influence well production will allow for the optimization of techniques to minimize the use of fresh water in hydraulic fracturing operations while improving the recovery of gas.

Ongoing Activity and Future Plans: In the coming months, the researchers will be conducting additional experiments on the available samples, including exposing the samples to flow back water from a real field setting. They will also be resuming work with ceramic-titania nanofiltration membranes and conducting membrane cleaning.

Lessons Learned: This project is ongoing. Lessons learned will be included in the final report upon project conclusion.

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Project Number: 11122-71

This is an active project; therefore, the final report is not available yet. However, more information about the project can be found at: http://www.rpsea.org/projects/11122-71/

Development of Subsurface Brine Disposal Framework in the Northern Appalachian Basin—Battelle Memorial Institute; 4/2013–3/2015

Objective: Growth in shale gas production and the associated increase in produced and flow back water disposal needs has fostered both current and projected demand for brine disposal wells in the Appalachian Basin. A systematic framework for fluid disposal management is needed to safely and economically meet this demand. The objective of this project is to help unconventional oil and gas producers meet this critical need by developing a geologic and operational framework for brine disposal in the Northern Appalachian Basin. By assessing aspects of geologic and reservoir management and conducting source-sink analysis to predict future regional brine-storage capacity, a robust framework will be developed to provide guidance for operators, hydrocarbon fuel producers, regulators, and public stakeholders.

Research Conducted: The Northern Appalachian Basin has a diverse range of injection zones. Maps of key zones have been prepared and integrated into a geologic framework model to illustrate subsurface distribution of key injection zones in the region. To evaluate injection zone properties, researchers performed a systematic review of available geophysical logs and estimated the gross and net thickness, average porosity, and porosity feet for each injection zone. They then tested rock cores from state libraries for injection formations and caprocks for hydraulic/geomechanical properties. Class 2 UIC brine disposal and monthly operational data was collected and analyzed. Reservoir performance was analyzed and the results of the geological analysis and operational data were evaluated for indicators of reservoir performance.

Accomplishments: Data was analyzed on brine disposal wells, geological conditions of injection zones, subsurface hydrologic conditions, geotechnical rock core test data, and operational data from injection wells for the Northern Appalachian Basin. The systematic analysis included 688 raster and 180 digital geophysical logs for Class 2 Brine Disposal wells in the study area.

Benefits: This project will assist producers with safe and economical disposal of produced fluids from unconventional onshore resources. This will help secure production from unconventional gas resources like the Marcellus and Utica Shale in the Northern Appalachian Basin. As brine disposal dwindles, costs rise, both of which can lead to the abandonment of operating wells, particularly if the costs to the well owner become greater than the benefits. This project will reduce brine disposal costs by highlighting disposal zones and operational parameters and building stakeholder confidence.

Ongoing Activity and Future Plans: Site-specific geocellular models and complete reservoir simulations of the injection process will be developed based on the results obtained from the data integration and analysis tasks. Source sink capacities will also be assessed. Practical guidance for injection operations will be developed and made available to industry and regulatory stakeholders.

Lessons Learned: Usually, the regional framework depicts the general setting for Class 2 brine disposal wells in the region investigated, while operational data provides typical range of parameters for brine injection wells based on injection formation. However, sometimes data merely reflects a specific well's activity.

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Project Number: 11122-73

This is an active project; therefore, the final report is not available yet. However, more information about the project can be found at: http://www.rpsea.org/projects/11122-73/

Cost Effective Recovery of Low-TDS Frac Flowback Water for Re-Use—GE Global Research; 10/2009–3/2011

Objective: Two significant barriers to the development of many shale gas plays are the lack of available water for drilling and hydrofracturing and limited disposal options for wastewater. This project evaluated technology that reduces the cost of treating flow back water for re-use in the hydrofracturing process. The primary objective of this project was to define a mobile, cost-effective, membrane-based process to treat frac flow back water with low levels of total dissolved solids (TDS) effectively enough that the water could be re-used as hydrofracturing fluid. The ultimate goal was to produce clean, reclaimed water suitable for re-use in hydrofracturing operations.

Research Conducted: The project team compiled data on the composition of flow back water and other characteristics across multiple shale plays. Researchers used the flow back composition data they collected to determine which shale would likely benefit from the membrane treatment processes. They also expanded the proposed product portfolio to include four additional options suitable for various re-use or discharge applications. Candidate pretreatment technologies were then evaluated at lab-scale and down-selected based on how effective they were at removing key contaminants. The chosen technologies were further validated with membrane fouling studies, using treated flow back water to demonstrate the technical feasibility of flow back treatment with reverse osmosis membranes. Process flow schemes were designed for each of the four product options using data based on experimental performance in actual flow back water treatment studies. For those products that required membrane treatment, researchers used membrane system modeling software to design enhanced water recovery beyond that of seawater desalination benchmarks. Finally, a parametric value assessment tool was created to account for temporal and geographic variability in flow back characteristics, local disposal costs, and regulations. This tool assessed the economic value of a given flow back recovery process relative to conventional disposal for any combination of anticipated TDS and local disposal costs.

Accomplishments: Experimental results confirmed that membrane systems, in combination with appropriate pretreatment technologies, could cost-effectively recover low-TDS flow back water. The recovered water is acceptable for beneficial reuse and safe surface discharge.

Benefits: This project tested and confirmed that membrane systems, in combination with appropriate pretreatment technologies, can provide cost effective recovery of low-TDS flow-back water for either beneficial reuse or safe surface discharge.

Ongoing Activity and Future Plans: This project is complete, and no further activities are planned.

Lessons Learned: The methodologies and technologies used for hydrofracturing were rapidly changing during the course of this project. Regulatory bodies were also in flux, and states were actively adjusting industry requirements with regard to water sourcing and disposal. These factors had a potentially large impact on the specifications and costs related to any final treated product identified by this study, particularly when it came to the quality level deemed acceptable for frac re-use. After performing a literature review and receiving feedback from operators, the team concluded that specifications for acceptable re-use are subject to change in the short-term depending on continual technology advances, operator experience and confidence, and upcoming regulations regarding discharge and re-use. Thus, it was necessary to update the product water scope to include four alternative final products with varying levels of purification:

- Product 1 (Clarified only): Suspended matter, free oil and grease, iron, and microbiological contaminants were filtered out.
- Product 2 (Softened and Clarified): In addition to purity levels for product 1, hardness ions—specifically barium, strontium, calcium, and magnesium—were removed
- Product 3: Partially desalinated to less than 20,000 ppm TDS (plus the purity specifications for Product 2)
- Product 4: Substantially desalinated to less than 500ppm TDS (plus the purity specifications for Product 2)

The initial product target was Product 3.

Bench-scale experiments successfully identified process technologies for the removal of key contaminants, as well as the associated operating conditions. However, removing organic contaminants from frac flow back waters proved more difficult than anticipated. The team solved the problem by using a novel ultrafiltration membrane.

Cost Effective Recovery of Low-TDS Frac Flowback Water for Re-Use—GE Global Research; 10/2009–3/2011

Key Contact: Harish R. Acharya, General Electric Global Research, 518-387-5875

Project Number: FE0000784

The final report for this project is available at: http://www.netl.doe.gov/File%20Library/Research/Oil-Gas/FE0000784_FinalReport.pdf.

A saline water disposal (SWD) well co-located with three hydrofractured wells.

Integration of Water Resource Models with Fayetteville Shale Decision and Support Systems—University of Arkansas-OSP; 10/2009–6/2013

Objective: Water supply issues have the potential to be major factors limiting natural gas recovery from shale and the growth of shale gas development. Water resource availability is affected by numerous factors, including demand for agricultural use, human consumption, and processes such as drought and changing climate. Oil and natural gas exploration, drilling, well completion, and production can affect surface and ground resources. A primary concern is the disposal of frac water and the possibility of negatively affecting local water quality. In the Fayetteville Shale play, all of these issues could be significant. Although these issues are widely agreed-upon, the science-based support systems and strategies that could assist the gas industry and regulatory agencies in managing water resources are lacking, particularly in the combined areas of drilling and hydrology. The absence of such strategies hinders the application of reliable regional-and basin- oriented shale gas development plans that could support regulatory streamlining and permitting.

This goal of this project was to develop a water-management decision support system by modifying and integrating a water resource simulation model with a modern enterprise geographic information system to provide a science-based tool to support development of energy resources in the Fayetteville Shale region.

Research Conducted: Relevant technologies and regulations affecting surface water in the Fayetteville shale play were researched and the resulting data were incorporated into the existing Fayetteville Shale Decision Support System (FSDSS) website. Researchers collaborated with the Arkansas Natural Resource Committee (ANRC) to identify specific regulatory and permitting issues. The Fayetteville Shale Information Site (FSIS) public map viewer was also updated to show the number of active, inactive, and permitted wells related to natural gas drilling activities by watershed.

Stream gauge records, daily weather records, and climate data were collected from the USGS and the National Weather Service and converted, along with GIS data layers, for use in the watershed case studies for SWAT simulations. Other previously-developed GIS data layers (DEM, hydrography, land use, land cover, soil, and geology formation maps) were also processed for use. Three representative case studies were identified for use in evaluating the effects of oil and gas operations on the stream flow within the Fayetteville Shale area using the SWAT model. The case study locations represent diverse hydrologic characteristics and were chosen based on biophysical settings and availability of historical stream flow records.

Accomplishments: The project provided information to the public and industry regarding water issues, and will lead to the development and implementation of quantitative tools for visualization and water management. Providing an open and transparent accounting of the water supplies will allow shale development by providing updated estimates of surface water availability while reducing potential adverse impacts associated with water usage for fracturing the shale.

Benefits: The results of this research are expected to significantly advance knowledge of how ground and surface water withdrawal (primarily for hydraulic fracture, but with the addition of public and agricultural use taken into account) affects water availability and quality in a watershed—specifically in the Fayetteville Shale Play. For example, an accurate map of all surface water, (i.e. retention ponds and small water bodies) covering a very large area will be made available; the effect of this usually unaccounted for water can be estimated. This could have a direct and immediate impact on natural gas producers who are considering the use of retention ponds as a source of water for use in hydraulic fracturing. This project provides the public with well-organized information at the intersection of gas-shale development and water use. To producers and regulators, it provides the ability to immediately share extensive, model-driven information about the effects of the development decisions they make.

Ongoing Activity and Future Plans: This project is complete, and no further activities are planned.

Lessons Learned: The team's automated mapping of small water bodies identified significantly more surface water than was previously found in national datasets. The small water body layer will play an important role in the FSDSS by determining how much water is retained in a watershed, and its development is expected to influence ANRC's surface water diversion permit decisions. Object-oriented imagery analysis has been used to locate and characterize retention ponds by using high-resolution, color-infrared aerial imagery of the entire Fayetteville

Integration of Water Resource Models with Fayetteville Shale Decision and Support Systems—University of Arkansas-OSP; 10/2009–6/2013

Shale area. Data processing began and drainage areas for each retention pond were computed. The newly-developed layer is able to capture the true shape, size, and location of the ponds. The results are seen as an improvement to the existing hydrology dataset.

Key Contact: Jackson Cothren, Center for Advanced Spatial Technology (CAST) at the University of Arkansas Fayetteville, jcothren@cast.uark.edu

Project Number: FE0000804

The final report for this project is available at: http://www.netl.doe.gov/File%20Library/Research/Oil-Gas/Natural%20Gas/fe0000804-final-report.pdf.

Water Management Strategies for Improved Coalbed Methane Production in the Black Warrior Basin—Geological Survey of Alabama; 10/2009–10/2013

Objective: The Black Warrior Basin of Alabama boasts a resource of between 10 and 20 trillion cubic feet of coalbed methane (CBM). CBM production results in large volumes of produced water that can be reused in CBM production or put to beneficial use by municipalities, industry, and agriculture. However, management of produced water requires appropriate regulatory structures to ensure that CBM is brought to market using environmentally sound practices. This study, led by the Geological Survey of Alabama in partnership with the United States Geological Survey and energy industry partners, will produce a high quality database and Geographic Information System (GIS) to analyze the environmental effects of produced water in the Basin.

Research Conducted: Team members obtained water samples and completed geochemical analyses on 25 of them to evaluate the relationship between water chemistry and geology within the unusually diverse environment of the Black Warrior Basin. Researchers also analyzed the production rates of different reservoirs throughout the study area, paying special attention to those with erratic performance. The team proposed that extraction rates might be enhanced through improved water management. The working group used GIS technology to map discharge points at which produced water is released into the Black Warrior River. Lastly, researchers analyzed the petrology throughout the study area to determine the relationship between geology and the formation of methane through bacterial methanogenesis.

Accomplishments: Reservoir performance was analyzed through decline curves and production mapping. Multiple types of production decline curves were identified with some found to be characteristic of specific producing areas. Areas where frequent well maintenance or water management issues have caused erratic production were identified and are indicative of inefficient gas recovery. Discharge points where processed water is released into the Black Warrior River have also been identified and incorporated into a GIS. Results of this study will be included in a special volume of the *International Journal of Coal Geology*.

Benefits: This study deepens understanding of the geology of the Black Warrior Basin, the use of produced water in CBM production, and the environmental impacts of produced water in the region. The knowledge gleaned will facilitate well-constructed regulations on the use and disposal of produced water to protect the environment while maximizing the potential of CBM reservoirs throughout the Basin.

Ongoing Activity and Future Plans: This project is complete, and no further activities are planned.

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Project Number: FE0000888

The final report for this project is available at: http://www.netl.doe.gov/File%20Library/Research/Oil-Gas/Natural%20Gas/fe0000888-final-report.pdf.

Sustainable Water Management of Flowback Water during Hydraulic Fracturing of Marcellus Shale for Natural Gas—University of Pittsburgh; 10/2009–01/2015

Objective: The Marcellus Shale in Pennsylvania has yielded substantial recovery of natural gas at manageable cost. However, hydrofracturing necessitates the use of up to five million gallons of water per well, usually drawn from local waterways and augmented with chemical additives. The flow back and produced water must be treated and disposed of. Until recently, most of this produced water was transferred to publically owned treatment works for disposal or for treatment so it could be reused as frac water. The University of Pittsburgh, in partnership with Carnegie Mellon University, sought to create a sustainable plan for the treatment of produced water in the Marcellus Shale play and to examine the potential of acid mine drainage (AMD) water as a supplement to flow back water in hydraulic fracturing. Researchers also studied the effects of barium sulfate on well surfaces and fracture spaces.

Research Conducted: Researchers created a holistic plan for the management of produced water at hydrofracturing sites, incorporating the use of AMD water. The location and availability of AMD and produced waters were assessed and their chemical compositions analyzed, leading to conclusions about ideal treatment processes. Additionally, the AMD database was updated to include flow rates and chemical analyses over time for 242 sites, which enabled scientists to consider the variability in flow and contaminant levels and database users to search for AMD sites based on desired flow rates, chemical analyses, and locations. The team then obtained and analyzed 160 samples of produced water and conducted water quality analysis at 140 AMD sites. Three different chemical equilibrium models were used to research the feasibility of removing metals from finished waters when AMD water was mixed with produced water. The team conducted bench-scale experiments in which produced water and AMD water were mixed and concentrations of barium sulfate in the finished waters were monitored.

Accomplishments: Coagulation and flocculation processes were optimized using two produced water samples from the Marcellus and locally available acid mine drainage. The team determined that final sulfate concentration levels were dependent on the barium content in the produced water and the mixing ratio of flow back water to AMD. Based on the bench-scale experiments, the clarifier and thickener were developed for pilot-scale testing in the field.

This project was also a finalist in the 2014 Shale Gas Innovation Contest. Results of this work have been presented at the Petroleum Technology Transfer Council Innovative Water Management Workshop in Morgantown, West Virginia.

Benefits: The use and reuse of AMD water in hydrofracturing could replace millions of gallons of water drawn from local streams, reducing production costs for natural gas recovery in the Marcellus. Withdrawing AMD from impacted PA streams would also improve the overall stream water quality in watersheds.

Ongoing Activity and Future Plans: The field-scale treatment system design was finalized and the system is being assembled in Tioga County, PA. Flowback water and AMD will be pumped from the flowback water tank and AMD tank, respectively. The flow rate will be monitored and adjusted to provide a desired mixing ratio of flowback water to AMD. The pH will be adjusted to achieve optimum condition as demonstrated in the bench-scale experiment. AMD will be added to the recycled sludge stream in the mixing tank and fed to the mixing reactor. Suspended solid formed in the mixing reactor will be removed by coagulation, flocculation, and sedimentation processes.

Lessons Learned: The team tested membrane filtration for separating precipitates in AMD and flow back water mixtures and discovered that the severity of membrane fouling decreased with an increase in the age of the flow back water. Experiments to test the affinity of barium sulfate for the sand proppant revealed that barium sulfate particles are captured by the sand in the front section of the column, resulting in an increase in pressure and a decrease in permeability. The effects are greater at higher flow rates. Experiments at a lower velocity resulted in less loss to permeability. The experiments were repeated with the proppant column in a vertical orientation.

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Project Number: FE0000975

More information about the project can be found at: http://www.netl.doe.gov/research/oil-and-gas/project-summaries/natural-gas-resources/de-fe0000975.

Zero Discharge Water Management for Horizontal Shale Gas Well Development—West Virginia University; 10/2009–3/2012

Objective: The objective of the project is to develop an on-site multi-media filtration system to beneficially reuse produced water. A five-stage modular design will permit efficient system operation and treatment of flow back water under conditions that vary over time.

Research Conducted: The team gathered engineering and water chemistry information and determined water quality requirements for frac water makeup by compiling information on hydraulic fracturing and shale gas production practices in Appalachian shale formations. Researchers tested whether filtration, which removes suspended solids but few dissolved solids, could be enhanced by coupling it with a process for removing salts. They examined various processes, including reverse osmosis, nanofiltration, and electro-coagulation (EC). Results indicated that the EC technology had a major effect on the distribution of solids, causing a shift from solids a few microns in size to larger solids with a single bell-shaped distribution. After successfully testing the process in the laboratory, the team designed, fabricated and deployed a mobile treatment unit (MTU) to complete two field trials, both under a lease agreement with Chesapeake Energy. The first location was a Utica Shale site in Carrollton, Ohio. The second was a Marcellus Shale site located near Wheeling, West Virginia. The capacity of the MTU sufficiently supported field operations at both sites and the MTU kept up with ongoing fracking operations.

Accomplishments: Over 600,000 gallons of water were treated during field tests with 98.6 percent of the water recycled. The remaining water was used to backwash the filtration units and then disposed of properly.

Benefits: Large-scale produced water recycling provides producers with significant cost savings, allowing industry to realize lower transportation and disposal costs and fewer environmental conflicts and risks of interruption to well development.

Ongoing Activity and Future Plans: This project is complete, and no further activities are planned.

Lessons Learned: The consistent quality of produced water used in the laboratory does not match the variable quality and quantity of the water delivered to a field site.

Media for the MTU needs to be more robust in its ability to capture oil and polymers before the mixture enters the lower modules of the filter. Processing influent with an oil-loving media before it enters the MTU will protect the lower modules from fouling and reduce the time required to backwash the unit to restore throughput at a reasonable inlet pressure. In addition, the project team learned that pairing a full-scale EC unit with the FilterSure system would be more cumbersome than they had originally envisioned, require its own mobile trailer unit and large power source, and cost more to obtain and operate than expected.

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Project Number: FE0001466

The final report for this project is available at: http://www.netl.doe.gov/File%20Library/Research/Oil-Gas/Natural%20Gas/shale%20gas/fe0001466-final-report.pdf.

Media testing of PDU for treating Marcellus RFW.

Water-Related Issues Affecting Conventional Oil and Gas Recovery and Potential Oil Shale Development in the Uinta Basin, Utah—Utah Geological Survey; 10/2008–4/2012

Objective: Saline water disposal must be addressed before petroleum and natural gas production can be increased in the Uinta Basin in Utah. Petroleum production increases result in commensurate saline water production increases; in order to protect the fragile environment of the basin, economically-feasible and environmentally-responsible disposal plans have to be put in place to address increased production. Current water disposal wells are near capacity, and new well permitting is being delayed until potential environmental impacts can be assessed. Producers have been particularly interested in using Birds Nest Aquifer for produced water disposal because it is one of the only large basins available. The Birds Nest Aquifer is poorly understood; the objective of this project was to characterize core samples from the aquifer and to generate maps that could be used to determine usable saline water disposal areas.

Research Conducted: This project was conducted in three phrases. In the first phase, researchers re-mapped the base of the moderately saline aquifer in the Uinta Basin. In phase 2, they created a detailed geologic characterization of the Birds Nest aquifer, a potential reservoir for large-scale saline water disposal. In the last phase, they collected and analyzed water samples from the eastern Uinta Basin to establish a water quality baseline.

Bird's-nest aquifer as exposed in outcrop, Evacuation Creek, Uintah County, Utah. This aquifer lies several hundred feet above the richest oil shale unit.

Accomplishments: With the same mapping techniques used during a previous mapping effort in 1987, the research team created a preliminary map of the base of the moderately saline aquifer (BMSA). They also completed preliminary maps displaying the areal extent and thickness of the Birds Nest aquifer. The Birds Nest zone in over 250 wells has been mapped on the aquifer's areal extent in central Uintah County. This first-of-its-kind map will greatly aid in determining potential Birds Nest aquifer saline water disposal areas. In addition, they interpreted digital geophysical logs from 258 wells throughout the Uinta Basin, picking the BMSA in each well; created detailed descriptions of all cores from the Birds Nest aquifer; and examined core containing the Birds Nest zone.

Benefits: Each phase of the study was designed to contribute to overall mitigation of the problems associated with produced saline water disposal, facilitate increased hydrocarbon production, and to identify environmentally-sound water disposal practices. GIS map development allows regulators and operators to make informed saline water disposal management decisions and protect fresh water resources.

Ongoing Activity and Future Plans: This project is complete, and no further activities are planned.

Lessons Learned: The researchers determined that the Birds Nest aquifer has significant potential as a large-scale saline water disposal zone. It contains highly saline water, a large amount of potential storage, and is relatively shallow, which will help reduce drilling expenses. Some challenges and risks unique to the basin will have to be addressed, however, including the risk that there may be large areas with no existing saline mineral dissolution. Also, it is not clear where water from the basin eventually goes; water migration will have to be better understood to ensure there is no environmental risk posed by saline water disposal.

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Project Number: NT0005671

The final report for this project is available at: http://www.netl.doe.gov/File%20Library/Research/Oil-Gas/Natural%20Gas/shale%20gas/nt0005671-final-report-uinta-water.pdf.

Effects of Irrigating with Treated Oil and Gas Product Water on Crop Biomass and Soil Permeability—University of Wyoming; 8/2008–9/2010

Objective: With decreasing water supplies available for irrigating crops, industry is looking to treat and reuse produced water from gas and oil drilling rather than disposing it. One concern with agricultural reuse of produced water is that treated produced water may reduce crop production and impact soil quality. The goal of this project was to study the impact of two parameters—salinity and sodicity—on crop production and determine the optimal blending ratio required for irrigating crops with produced water.

Research Conducted: The researchers used different pretreatment methods followed by ion exchange, reverse osmosis, or electro-dialysis reversal to maintain the long term physical integrity of representative soils from the Powder River Basin (PRB) and achieve normal crop production. The researchers used two (2) treatment strategies to clean oil and gas produced water: (1) physiochemical pretreatment (DAF + organo-clay) followed by DT RO or (2) physiochemical pretreatment (DAF + organo-clay) followed by EDR to reduce organic and inorganic constituent loads in oil and gas produced water. The treated water was added to three representative soil types from the PRB. Two representative plant species grown in the PRB—alfalfa and western wheatgrass—were irrigated with a range of treated produced water and a range of treated blends.

Accomplishments: The research team studied available produced water treatment technologies and the effects of irrigating with highly saline and/or sodic water sources. The researchers found that plant production levels resulting from untreated coalbed natural gas (CBNG) produced water were significantly higher than untreated conventional oil and gas produced water; however, little difference was found between water treatments. There was no significant difference between the 100% treated produced water and river water, which served as a control.

Benefits: This project provided comprehensive data on blending ratios that can be coupled with produced water treatment technologies to ensure productive long-term irrigation strategies. This knowledge is helping managers optimize produced water treatment to ensure high crop yields.

Ongoing Activity and Future Plans: This project is completed and no further activity is planned.

Lessons Learned: One unexpected result of the project was that some of the alfalfa and western wheatgrass plants contained high levels of boron; these levels may have resulted from either soil or irrigation water containing high boron levels.

Key Contact: Terry Brown, Western Research Institute, tbrown@uwyo.edu, 303-226-8524

Project Number: NT0005681

The final report for this project is available at: http://www.netl.doe.gov/File%20Library/Research/Oil-Gas/NT0005681_FinalReport.pdf.

Innovative Water Management Technology to Reduce Environmental Impacts of Produced Water—Clemson University; 11/2008–5/2013

Objective: Produced waters resulting from gas and oil drilling can contain a wide range of constituents of concern, including metals (e.g., iron, manganese, and zinc) and organics (e.g., low molecular-weight aromatic hydrocarbons such as benzene and toluene). Targeting such a wide range of constituents for treatment presents challenges. For example, reverse osmosis is sometimes used to reduce cation and anion concentrations in produced waters, but it is not effective in reducing ammonia concentrations; as a result, additional treatment to reduce ammonia is needed. The main objective of this project was to design and construct a pilot-scale constructed wetland treatment systems (CWTS) at Clemson University based on fundamental reactions and processes needed to treat targeted constituents.

Research Conducted: Researchers conducted toxicity tests of the treated produced water with several animal species, including the freshwater water flea (*Ceriodaphnia dubia*) and the flathead minnow (*Pimephales promelas*). They then constructed pilot-scale wetland treatment systems, based on fundamental reactions and processes needed to treat targeted constituents in produced waters. The team investigated four waters, comparing a range of characteristics or constituents of concern for treatment including metals, metalloids, oil and grease, and ammonia.

Based on the data collected during the pilot-scale experiments, the project team designed and constructed a demonstration wetland treatment system at a coal bed methane field in northern Alabama.

Accomplishments: Toxicity tests demonstrated that survival was significantly better with the treated produced water. Pilot-scale systems were designed to produce biogeochemical conditions that result in targeted treatment pathways for constituents that occur in produced waters. Using the demonstration systems, they tested the impact of both untreated and treated water on plants (corn, cabbage, and soybean) and animals (water flea and flathead minnow).

During field tests, scientists measured conductivity in the produced water holding tank and monitored the performance of the system with sampling and analytical methods designed to calculate removal efficiency, removal rate, and removal extent of the constituents of concern.

Analyses of inflow and outflow water samples indicated ammonia was successfully removed from the wetland during all sampling periods; Barium removal was over 90 percent of inflow concentrations until the sulfate concentrations decreased in the wetland cells. Cadmium and iron were removed from the wetland to desired levels, while manganese removal varied over time.

Lessons Learned: Results of the pilot scale constructed wetland systems for treating post reverse osmosis produced water indicated that the outdoor control system could not match the level of performance comparable to that of the indoor control systems. Thus, water and air temperatures are important considerations when designing a CWTS for treating post-RO produced water.

Benefits: Treatment performance results indicated that CWTSs can be designed and built to promote specific environmental and geochemical conditions for targeted biogeochemical pathways to operate. This will allow technologies to be developed that target specific produced water constituents.

Ongoing Activity and Future Plans: This project is completed and no further activity is planned.

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Project Number: NT0005682

The final report for this project is available at: http://www.netl.doe.gov/File%20Library/Research/Oil-Gas/Natural%20Gas/nt0005682-final-report.pdf.

Predicting Composition and Volumes of Produced Water—NETL ORD; FY2015

Objective: This project involves predicting the composition and volume of waters produced during shale gas development and, more specifically, identifying the factors that affect the volume and composition of byproduct water generated from hydraulic fracturing in unconventional formations and evaluating the potential to reduce the need for new freshwater resources for hydraulic fracturing.

Research Conducted: Research using existing reservoir modeling tools has been used to estimate the composition and volume parameters for produced waters. The research team has estimated leakoff and flow back rates and salinity at different time steps of flow back via development of a (1) coupled model that can simulate fracture propagation, proppant distribution, and fluid cleanup in a naturally-fractured shale reservoir; (2) sets of equations to handle two phase (gas/water) flow and behavior under hydraulic fracturing scenarios, and (3) finite-difference approximations to solve for pressure and fluid saturations, characterization of the stimulated and propped fracture network, and salt dissolution kinetics and mixing. Research was also conducted to optimize water use and reuse in order to decrease the environmental risks associated with unconventional fossil resource production.

Accomplishments: Current accomplishments include completion of a draft model integrating flow back system attributes for predicting the volumes and compositions of water produced from hydraulic fracturing of gas shales. The research team also completed a robust and detailed produced water model for predicting the composition/volume of water based on validation with Appalachian Basin data.

Benefits: An ability to estimate the potential composition and volume of produced water prior to actual field activities will provide inputs for identifying potential management strategies that can be deployed to minimize freshwater use for hydraulic fracturing. Successful completion of this project will provide insight into development of regional-scale strategies for management of aqueous byproduct streams from hydraulically fractured shale development in the Appalachian Basin.

Ongoing Activity and Future Plans: Subsurface modeling of produced water composition and volume focused on both stochastic and numerical modeling approaches. Results from the stochastic (data mining) approach revealed that different geological groups resulted in different relationships among shut in time, treatment rates, and water recovered from hydraulically-fractured shale formations. The numerical modeling approach was expanded from a 2-dimensional to a 3-dimensional format and validated, and the "chemistry module" for predicting composition was calibrated. Work with the proppant transport model showed that though larger proppant size resulted in a greater stimulated area, a lower reservoir flow back rate was observed. Optimization modeling for produced water re-use focused on defining the path forward for linking the optimization model approach with environmental benefits. Future modeling work includes determining the schedule, time, and location for pipeline installment, capacity and location of water impoundments, and location of centralized treatment facilities and treatment units as well as documentation and dissemination of results related to the produced water volume and composition prediction models.

Lessons Learned: Research on optimizing scenarios to minimize fresh water use was initially focused on determining a fracturing schedule and flow back reuse at each wellpad that minimizes costs associated with transportation (pumping and trucking), treatment, disposal, and storage, while maximizing revenue generated from production of the wellpads. It was determined to optimize future scenarios on environmental impact minimization.

Key Contact: Robert Dilmore, U.S. DOE NETL

Project Number: Task 3

More information about this and related ORD research projects can be found at: http://www.netl.doe.gov/research/on-site-research/research-portfolio/oil--gas-research/ucr

Evaluation of the Geochemical and Microbiological Composition of Shale Gas Produced Water and Solid Wastes—NETL ORD; 9/2014

Objective: The objective of this project is to characterize the chemical and microbiological transformations that occur during water treatment (for reuse) and the temporary storage of produced water in on-site tanks and impoundments in shale gas development operations. Also assessed is the potential release of toxic constituents to groundwater, soil, or atmosphere when produced water sludge is in landfills or buried at the drill site.

Research Conducted: Research being conducted under this task is divided into four categories: (1) geochemistry of radium in produced water from unconventional gas development, (2) leaching of chemical species from waste solids (produced water treatment residuals and drill cuttings) under simulated landfill conditions, (3) monitoring response of brine-adapted microbes to changing conditions typical of unconventional gas development, and (4) determining the role that microbes might play in the mobility of Naturally Occurring Radioactive Material (NORM) in the landfill environment. Water and sludge samples were taken from temporary produced water storage tanks and impoundments and characterized for chemical constituents including NORM and microbial ecology.

Accomplishments: Previous accomplishments include an improved understanding of the complex microbial consortia that exist in storage ponds constructed for temporary storage of flow back and produced water. Taxonomic evaluations of these waters have identified a diverse population which, in turn, has provided insight into the chemical transformations (particularly those of redox sensitive species such as uranium and iron) that occur during storage. This knowledge will enable industry to manage the ecology of produced water storage ponds in way that will encourage the growth of microbes that catalyze positive chemical transformations. Researchers at the University of Pittsburgh working under this project developed a new method for analyzing the radium content of highly saline waters that reduced the time required for radium analysis from ~30 days to one day.

Current accomplishments include the development of a simulated leaching protocol to determine the fate of residual solids when disposed in landfills under a range of environmental conditions. Experimental results from leaching tests are being developed into conference presentations and journal publications.

Benefits: Understanding the reactions between shale and hydraulic fracturing fluids, and the effect of geochemical and microbiological reactions on produced water will enable industry to develop better environmental management practices for produced water.

Ongoing Activity and Future Plans:

- The research team developed calculations to evaluate the Total Effective Dose Equivalent and Marcellus region realistic NORM exposure scenarios.
- New methods for ascertaining the leachability of produced water treatment residuals in flow back water are being evaluated.
- Plans to expand microbiological analysis of produced waters to include samples from the Bakken (in collaboration with North Dakota State University) were developed. Samples from additional flow back water ponds in the Appalachian Basin (from two different operators) were evaluated.
- Active microbial communities in produced waters, and their ability to reduce soluble uranium (VI) to insoluble uranium (IV), were investigated through enrichment cultures. Abiotic reactions were found to be the primary control on uranium (VI) reduction; this reaction pathway is being further investigated with native flow back water.

Future work includes completing full report of past work related to NORM measurement and mobility of radium; an evaluation and report on the results of leachability studies of treatment solid residuals under landfill conditions, including evaluation of drill cuttings used in roadways, and a report on genomic sequencing of produced waters from Marcellus and other shale plays.

Lessons Learned: Samples from the hyper-saline, sulfate-reducing enrichments have been plated and after three weeks of incubation, odd colony morphology has appeared on several plates. The plates contain colonies that appear to propagate as rectilinear forms. This odd morphology has only been observed in one other species, a strictly aerobic Archaea.

Key Contact: Richard Hammack, NETL

Project Number: Task 8

Evaluation of the Geochemical and Microbiological Composition of Shale Gas Produced Water and Solid Wastes—NETL ORD; 9/2014

More information about this and other ORD research projects can be found at:

http://www.netl.doe.gov/research/on-site-research/research-portfolio/oil--gas-research/ucr

Biogeochemical Factors that Affect the Composition of Produced Waters and the Utility of Geochemical Tracers Tools—NETL ORD; FY2015

Objective: Produced waters from oil and gas operations, including unconventional shale reservoirs, are treated by various techniques to prepare waters either for re-use or disposal. Although many potential contaminant species can be removed from the liquid phase during these treatment processes, the residual solids may require additional treatment prior to disposal due to precipitation of contaminant and naturally-occurring radioactive material (NORM) during the initial treatment process. The objective of this effort is to develop source term data sets that can be used for modeling of potential leachates from shale gas production waste solids, to obtain detailed knowledge of parameters that may be important considerations when using alternative fracturing fluids, and to develop controlled experimental data sets that can be used to constrain field-based geochemical tracer measurements.

Research Conducted: The team conducted research under four subtasks to determine the lithological sources of geochemical tracers and potential contaminants, the reactions that control the release or retention of these species within the shale formation, the fate of the fracturing chemicals downhole, and the effect of biogeochemical reactions on the geomechanical properties of shales.

Accomplishments: Selected current accomplishments include the following:

- Sequential extraction studies with shale samples confirmed that most of the uranium and arsenic in shales is contained either in organic matter/sulfide fractions (oxidizables) or in silicate residues. Geochemical profiles of shale core and outcrop samples showed a correlation between redox-sensitive elements and sulfidic minerals, and isovalent elements and silicate melts.

- Validation of rare earth element (REE) analysis via liquid-liquid extraction (LLE) and seaFAST methods continued. Sequential extraction results showed that most REEs in the Marcellus Shale are associated with the organic fraction. Phase association is anticipated to determine the level of REE mobility from shale, and their overall patterns that can be used for hydrologic tracer studies. Modeling of geochemical tracers has been focused on strontium isotopes, where a predictive model has been developed to characterize strontium isotopic signatures expected in surface and ground waters if Marcellus produced water leaks or spills.

- Cation exchange capacity (CEC) experiments showed that: CEC values in Marcellus and Utica Shale are low and represent shales dominated by illite, with little to no smectite; CEC values in the Utica shale are lower than the Marcellus shale despite slightly more expandability in the Utica shale; CEC values do not correlate to total uranium in the shale; and CEC values measured at room temperature and at reservoir temperature are statistically the same.

- Flowback fluid microorganisms were evaluated for carbon utilization via a variety of microbiological and chemical analysis techniques. Laboratory methods were developed in the laboratory for chemical analysis of the organic constituents in frac fluids. Experimental work showed that certain biocides used during hydraulic fracturing are able to react via hydrolysis, and reactions with pyrite.

In addition, the team determined isotope and geochemical signals that can be used and modeled (individually or in combination) to identify the sources of geologic fluids and association (if any) with Appalachian Basin shale development.

Benefits: An understanding of the potential sources of the contaminants found in residual solids, and their biogeochemical behavior in shale gas reservoirs, may aid in designing better reservoir and produced water management strategies.

Ongoing Activity and Future Plans: Future efforts include completing reports detailing results on contaminant sources and potential mobility in shale reservoirs; multi-parameter modeling of multiple geochemical signals for evaluating sources of geologic fluids; and the effects of fluid-shale interactions on physical properties of shales. Complete reporting on tracer development and contaminant identification efforts from prior calendar years.

Lessons Learned: Several experiments were conducted to demonstrate the effectiveness of a modified LLE technique for separation and pre-concentration of REE from small-volume samples of hypersaline brines. The modified procedure increases recovery for all elements, especially the light REE. High recovery of the heavy REE remains a challenge; however, previous analyses suggest that quantitative recovery can be achieved by either increasing the volume of acid used to elute the REE or adding an additional elution step.

Biogeochemical Factors that Affect the Composition of Produced Waters and the Utility of Geochemical Tracers Tools—NETL ORD; FY2015

Key Contact: Alexandra Hakala, NETL, Alexandra.Hakala@netl.doe.gov

Project Number: Task 9

More information about this and other ORD research projects can be found at: http://www.netl.doe.gov/research/on-site-research/research-portfolio/oil--gas-research/ucr

An Integrated Water Treatment Technology Solution for Sustainable Water Resource Management in the Marcellus Shale—Altela, Inc.; 10/2009–4/2011

Objective: The goal of this project was to address the increasing water resource challenges caused by natural gas production that affect other water stakeholders in shale gas basins, with a primary objective of demonstrating that the AltelaRain® technology could be successfully deployed in the Marcellus Shale Basin to treat frac flow back water. Specific goals of the project were three-fold:

(1) Demonstrate in the field that a water treatment technology is capable of treating Marcellus frac water to meet the quality standards required for discharge or applicable beneficial reuse.

(2) Deliver field-proof that the water treatment technology could economically treat frac water at a cost equal to or lower than other disposal methods currently available.

(3) Demonstrate that the regulatory environment would support implementation of the water treatment technology solution.

Research Conducted: To verify that the technology was capable of treating Marcellus frac water to within water quality standards required for discharge or applicable beneficial re-use, field water samples were taken from two well locations in Butler County, Pennsylvania, and produced water was sampled from the Ross Well site in New York by an independent third party, CWM Environmental, Inc. Four 55-gallon drums of produced water were filled on-site and transported to Altela's Albuquerque facility for testing. Additionally, a small quantity of this raw water was analyzed by CWM Environmental, Inc.'s water testing laboratory to determine the chemical constituents before testing by Altela. Four barrels each of frac and flow back water were also pulled from the Bergbigler Well and shipped to Altela. Raw water samples were again analyzed by CWM Environmental, Inc. before being subjected to Altela's test-bench testing.

Each raw sample was "treated" over a 3-day period using the same equipment and test tower, with each sample requiring about a day on the tower. The samples were treated by circulating them through the Altela tower until they reached a pre-determined residual volume. Pure water was evaporated from the raw water solution during the process, resulting in a concentrated version of the raw solution. Upon completion of all three test-bench tests, a sample from each of the three net solutions (raw water, a concentrated sample, and clean water) was taken for applicable mass balance analysis.

Once the technology was proven, the Altela 4000 system was installed and became fully operational on July 22, 2010. By April 8, 2011, over 299,040 gallons of Marcellus Shale frac flow-back water had been treated and purified at the well-site, resulting in the production of 200,215 gallons of clean distilled water.

Accomplishments: Through nine continuous months of operation, the AltelaRain® system—placed adjacent to a natural gas well—treated 77 percent of the frac flow back and production wastewater on-site, providing distilled water as the product. In general, the distilled water quality was exceptional, regardless of the raw water solution make-up or net concentration of dissolved salts in the raw water. This result validates the AltelaRain® technology for treating the various solutions associated with natural gas production in the Marcellus Shale. The total barrel operating cost was $0.12/gallon, or $4.88/barrel, representing a minimum cost savings of 23 percent as compared to conventional truck and disposal fees at commercial facilities or UIC reinjection wells.

The results showed the technology successfully cleaned the samples, meeting or exceeding the Pennsylvania Department of Environmental Protection's water quality requirements, as applied to the latest NPDES permit.

Benefits: Because the AltelaRain® technology does not require pressure—the process can be driven by economical sources of low-grade heat, waste heat, or natural gas and is suitable for cogeneration applications to reduce energy costs. In addition, operating and capital costs are low.

Ongoing Activity and Future Plans: This project is complete, and no further activities are planned. As a result of this project, four AltelaRain modules were sold and installed at a water treatment facility in Williamsport, Pa., where they were treating almost 100,000 gallons of wastewater every day. In addition, Altela and its joint venture partners opened two new plants in 2012 for treating, recycling, and disposing of Marcellus shale wastewater located in Clarion and McKean Counties in western Pennsylvania.

Lessons Learned: The team discovered multiple reasons why the on-site demonstration treatment rates were initially lower than expected. The towers operated best when they were supplied with a constant supply of steam. The research team discovered that the Ajax boiler could not meet that requirement because it is an on/off style and not a modulated flame boiler. In addition, the system was designed to operate on 14 towers; the team discovered that it only could operate on 10 towers at one

An Integrated Water Treatment Technology Solution for Sustainable Water Resource Management in the Marcellus Shale—Altela, Inc.; 10/2009–4/2011

time. The first demonstration towers were accepting more steam than was originally thought. Although each tower demonstrated a greater capacity at maximum operating conditions than originally expected, the system's boiler was under-sized for the full complement of 14 towers. Even though the boiler was designed to supply a steam output of 690 lbs. /hr., it was running 15percent higher than the amount of steam needed to operate the 14 towers and at the high end of its operating limits. Carry over from the boiler into the towers lowered the performance significantly.

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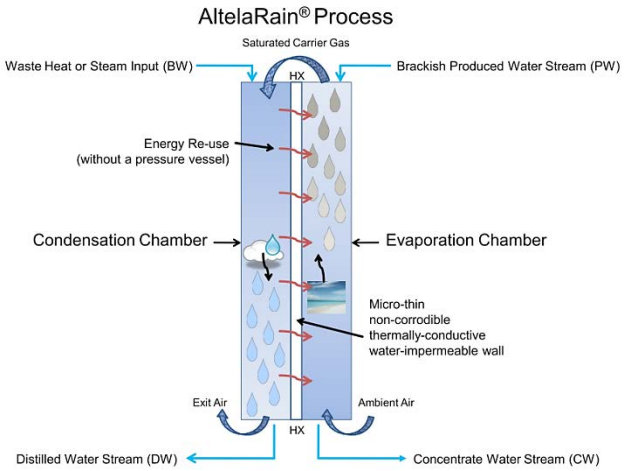
Project Number: FE0000833

The final report is available at: http://www.netl.doe.gov/File%20Library/Research/Oil-Gas/Natural%20Gas/shale%20gas/fe0000833-final-report.pdf.



Membrane Technology for Produced Water at Lea County, NM—Lea County Government; 10/2008–6/2011

Objective: Gas and oil drilling in Southeastern New Mexico (SENM) generates roughly 400 million barrels per year of produced water. This produced water contains high concentrations of total dissolved solids (TDS); the TDS concentration can be as much as 6 times greater than the concentration in seawater. Typically, produced water is transported off-site and injected into injection wells or disposal ponds at an average cost of about $1.2 billion per year.

Because fresh water is scarce in New Mexico, effective processes for cleaning and reusing water from industrial processes are especially important. The goal of this project was to develop a prototype desalination system that can remove the salts from gas and oil drilling produced water so the water can be reused by industries in SENM, including potash producers. The prototype system includes both a pretreatment process (where suspended solids and organics, hydrocarbons, and microorganisms are removed to reduce the chances of membrane fouling) and treatment processes (forward osmosis).

Research Conducted: This project consisted of three phases: a technical investigation to identify a technology for desalinating water, a field demonstration of the identified technology, and an economic analysis and commercialization plan to determine large-scale production feasibility. As part of the economic analysis, the research team considered the cost of powering the desalinization system; their review included effectiveness and cost comparisons for alternative energy sources (like wind and solar energy).

Accomplishments: Laboratory tests demonstrated that produced water with TDS as high as 200,000 ppm be desalinated. The pilot-scale pretreatment/forward osmosis desalinization field tests demonstrated that the design could be scaled up. Large-scale systems for desalinating produced water could be implemented once engineering issues are resolved and a cost-effective, low-impact energy source is selected.

Benefits: This project has the potential to transform produced water from a by-product of gas and oil drilling into a reusable resource. One local benefit would be the use of treated water for potash production. Although New Mexico ranks first in the United States in potash production, water is a necessary component. Using treated produced water rather than fresh water would be beneficial.

Ongoing Activity and Future Plans: This project is complete, and no further activities are planned.

Lessons Learned: The field demonstration unit processed about 2 gallons per hour or 48 gallons per day of produced water. To meet the demands of the potash industry, the system would have to be scaled up 167,000 times to reach 8 million gallons per day.

The team determined that the Aquastream/CTI pretreatment process performed well during field testing based on chemical testing; however, it was not clear that the Aquastream/CTI process was the best overall process. During the course of research, the team explored other processes that may be able to remove a wider range of contaminants than Aquastream/CTI, but the most promising of those projects presented engineering issues associated with scaling and excessive energy consumption.

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Project Number: NT0005227

The final report for this project is available at: http://www.netl.doe.gov/File%20Library/Research/Oil-Gas/nt0005227-final-report.pdf.

Placement of the mixing tanks in the trailer.

The Technology Integration Program: An Extension of the Environmentally Friendly Drilling Systems Program—Houston Advanced Research Center; 7/2012–7/2015

Objective: The Environmentally Friendly Drilling – Technology Integration Program (EFD-TIP) represents an integrated approach to applying new technologies to unconventional gas production. The program coordinates technology development as opposed to individual projects that originate from a variety of sources. The EFD-TIP has a broad mission: to identify and facilitate the integration of projects and programs that can affect unconventional natural gas development in economical and environmentally sensitive ways. The following goals are designed to achieve that mission:

- Speed commercial development of technology.
- Create an organizational structure that includes a network of regional centers to facilitate and coordinate field deployment of technologies and document the effectiveness of field operations.
- Perform technology field trials so results can be evaluated efficiently to benefit organizations in the industry and public sectors.
- Document and provide the results of technology field trials so that promising processes, systems, and products are available for a wider range of unconventional natural gas plays.
- Emphasize programs that reduce cost and improve performance, reduce the environmental impacts, and address societal issues associated with unconventional natural gas development.
- Include and report safety improvements in the planning and demonstration of technologies, and emphasize technologies that foster a culture of health, safety, and environmental protection.

Research Conducted: The EFD-TIP established regional centers to provide unbiased science relevant to local, regional, and national policies and to conduct case studies on the application of selected technologies. A diverse advisory committee was formed, with operators, service companies, regulators, environmental organizations, and other subject matter experts serving to evaluate ideas, identify field test sites, and ensure the relevance of various project tasks. A subcontractor evaluated all prior RPSEA projects, ranking the projects' technologies using a technology readiness assessment method. Regional leads also flagged DOE technologies for inclusion and identified potential field test sites in West Virginia, Ohio, and Colorado for demonstration projects.

Accomplishments: HARC is measuring how environmental issues are addressed using a variety of tools. The team combines technology road mapping to identify, environmental impact mitigations to evaluate, inter-state collaborations to coordinate efforts, and workforce development initiatives to educate the practices of current and future employees.

The team has developed an online virtual rig and a virtual hydraulic fracturing website using state-of-the-art gaming software and graphics applications. They have also created a mobile membrane testing lab and are assisting with the development of wireless sensor networks for monitoring volatile organic compounds at drilling sites.

EFD-TIP is also involved in a temporal study in a Texas county with intense drilling activity in the Eagle Ford shale. The study is evaluating the possible environmental impact of oil and gas operations occurring just across the fence line of a landowner's property. Air, water, and soil samples are taken every three months and analyzed for possible contamination. This case study is part of a larger program to identify new analytical techniques and field operational practices to lower the environmental impact of drilling and production in sensitive ecosystems.

The team is also performing field tests to monitor air emissions, ground water, erosion/sedimentation, wildlife impacts and landscape changes.

Benefits: Benefits of technology transfer and other specific activities included in the scope of this project include reducing the environmental footprint from energy development through the development and commercialization of new technologies, methods, and engineering techniques. Additional benefits are myriad and include reduced costs for consumers, producers, and suppliers, and improved public perception of the oil and gas industry.

Ongoing Activity and Future Plans: The project team will explore how other shale characterization projects can be incorporated into the TIP demonstration efforts and will continue to advance the commercialization of successfully demonstrated projects. Additionally, EFD-TIP will work with academic researchers to appraise the social impacts of proposed gas

The Technology Integration Program: An Extension of the Environmentally Friendly Drilling Systems Program—Houston Advanced Research Center; 7/2012–7/2015

development in the Eagle Ford Shale using data gathered from recently conducted sociological studies in the Barnett Shale. The focus will be on identifying, documenting, and addressing the social, cultural, demographic, economic, and social-psychological aspects elucidated in the study. Project researchers will also plan, deploy, conduct, and document a field trial to monitor air quality in the Eagle Ford Shale. In addition to this and other work in support of the mission, the EFD-TIP continues to advance the established website and network of publications, articles, workshops, and conferences.

Lessons Learned: Barriers to technology implementation were listed during the first phase of the project. The project team learned that securing a field test site presented a significant barrier, particularly to promising technologies managed by universities without ready access to a site. Even after a field test site is identified, opportunities may be lost in the time required to obtain permits, meet regulatory requirements, and institute required safety training; however, this problem can be overcome by demonstrating multiple technologies at a single site.

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Project Number: 10122-06

More information about this project can be found at the project's website: http://efdsystems.org/index.php/efd-technology-integration-program-efd-tip/

Or at the RPSEA website: http://www.rpsea.org/projects/10122-06/

Pilot Testing: Pretreatment Options to Allow Re-Use of Frac Flowback and Produced Brine for Gas Shale Resource Development—Texas A and M University, Engineering Experiment Station; 10/2009–12/2012

Objective: Many shale gas wells are horizontal wells, requiring up to 10 million gallons of water for completion. A major obstacle to reusing the produced water from these wells is the presence of contaminants that, if not removed, will both prevent re-use and hinder disposal. The challenge is to conserve limited supplies of freshwater by identifying technologies and approaches for treating the produced water from these wells for beneficial re-use in other applications or subsequent wells. This project addresses these challenges via development of a mobile and multifunctional pre-treatment process for field-produced brine and fracture flow back waters. The objective was to design a cost-effective and reliable water treatment technology specifically for pre-treating field waste brine and to conduct a side-by-side comparison between the new technology and technology currently used in field operations.

Research Conducted: The project team employed a GPRI Designs™ Desalination Technology mobile treatment trailer to filter ultra-high salinity brine. The trailer employed a multi-stage treatment train to evaluate eight different components of filtration, including two types of oil and grease removal; one benzene, toluene, ethylbenzene, and xylene removal step; three micro-filters; and two different nanofilters. Each technique was measured by its separation efficiency, power consumption, and ability to withstand fouling. Field trials for media filtration showed that it removed hydrocarbons from the produced water satisfactorily. Micro-filtration trials to remove total suspended solids (TSS) were run with ultra-filtration membranes that could be reverse-washed to reduce fouling. For these tests, filtration rate was measured as a function of throughput (elapsed time) and then turbidity was monitored. Finally, the output flow rate was recorded at periodic intervals. Pressurized hollow fiber, ceramic, and stainless steel membranes offered the best results. Two nanofilters were used to selectively remove alkalinity and specific dissolved materials. Both were effective in removing ions and both produced good flux at low pressures and low power.

Accomplishments: The trial processed ultra-high salinity brine containing greater than 140,000 total dissolved solids, successfully removing them as well as all hydrocarbons, bacteria, and TSS, so that nano-filtration with spiral wrapped polymeric membranes was able to subsequently remove divalent dissolved ions. The treated produced water was thermodynamically stable and suitable for re-use in subsequent well operations. Pretreatment technologies for deployment in field operations were identified and tests were replicated at three locations. Researchers found the results from all locations validated the performance of the pre-filtration process train. They also determined operating costs, separation efficiency, and product water quality. Researchers processed over 6,000 gallons of produced water.

A major accomplishment was the development of a chemical-free methodology for removing contaminants from highly-salinated produced water. Overall, the project objectives were met, as the team successfully identified the most promising types of technology for pretreating hypersaline produced water. The results show that suspended solids contamination could be removed by membrane processing rather than traditional means.

Benefits: The mobile, multifunctional water treatment and comprehensive analytical test program provides on-site monitoring of the process. The chemical-free method developed by the project team can help manage produced water from Marcellus gas shale and other wells in an environmentally-friendly and cost-effective way. This will benefit the communities and the environment by protecting freshwater sources and the industry by reducing costs.

Ongoing Activity and Future Plans: This project is complete, and no further activities are planned.

Lessons Learned: Although all tested micro filters clarified the brines, the hollow fiber configuration was preferred because it offers high membrane packing densities, sanitary designs, and an ability to withstand permeate back pressure. These benefits allow greater flexibility in system design and operation. The geometry enables a high membrane surface area in a compact module, which allows large volumes of produced water to be filtered in minimal space, with low power consumption. Disadvantages are that this module is intolerant to large pressure changes and is readily plugged by particles. Because high-salinity produced water from the Marcellus wells was not available to researchers, an additional objective was established for this project: identify and test ultra-high salinity produced water from the Herkimer formation. Produced water from the Herkimer represents an analog to Marcellus brine and can be used to characterize Utica Shale brines.

Key Contact: Dave Burnett, Texas A&M University, 979-845-2274, burnett@pe.tamu.edu.

Pilot Testing: Pretreatment Options to Allow Re-Use of Frac Flowback and Produced Brine for Gas Shale Resource Development—Texas A and M University, Engineering Experiment Station; 10/2009–12/2012

Project Number: FE0000847

The final report for this project is available at: http://www.netl.doe.gov/File%20Library/Research/Oil-Gas/Natural%20Gas/fe0000847-final-report.pdf.

Risk Based Data Management System (RBDMS) and Cost Effective Regulatory Approaches (CERA) Related to HF and Geologic Sequestration of CO2—Groundwater Protection Council; 10/2009–9/2016

Objective: The Risk Based Data Management System (RBDMS) was developed by the Ground Water Protection Council (GWPC) and is an essential tool for managing oil and gas activities and evaluating the risk to source water in 22 states. Still, better strategies are needed to ensure the protection of clean groundwater and the development and use of energy as demands for both continue to increase. The objective of this project is to enhance the RBDMS by adding new components related to the environmental topics associated with hydraulic fracturing (HF) and by managing data related to oil and natural gas well histories, production, produced water disposal, enhanced recovery, reporting, stripper wells, and other operations with the goal of protecting ground water resources.

Research Conducted: The project team maintained and updated the FracFocus website and assessed the regulatory and data needs for carbon dioxide (CO2) geosequestration. The GWPC also assisted in reviewing and updating the State Review of Oil and Natural Gas Environmental Regulations (STRONGER) guidelines, expanding them to include air quality and addressing other issues in the HF sections in addition to conducting additional state reviews. For example, a STRONGER review team met with Pennsylvania state program management teams to review HF rules and guidelines. They reviewed oil and gas regulatory programs and posted the reviews on STRONGER website. The team also performed a state needs assessment for regulation of CO2 geosequestration, and created an online state catalog of exploration and production best management practices. The GWPC updated the FracFocus website to version 2.0, which includes a database with increased search capabilities. The website allows states to download data from FracFocus and import it into their own database systems for regulatory reporting.

Accomplishments: The Colorado Gas Conservation Commission (COGCC) was awarded the Innovation Award for Natural Resources by The Council of State Governments in recognition of the eForm permitting system. The system was developed by the COGCC and the GWPC as part of this project, and has reduced permit processing time by enabling operators to complete regulatory forms online. Additionally, the RBDMS HF module has been incorporated into both RBDMS.net and the eForms modules. Five states have incorporated portions of the HF module into their existing RBDMS programs. Over 40,000 well disclosures have been uploaded into FracFocus and the website is in use by multiple states. The team has also developed a web-based GIS model that assesses water management options using existing and enhanced RBDMS analytical capabilities.

Benefits: Benefits from this project include an enhanced ability to submit well data electronically, and better access to a training framework for technical and regulatory needs. The results of this project will enhance the RBDMS to enable more efficient data transfer between state agencies and industry operators. The HF module is a valuable decision-making aid for assessing potential impacts to the environment.

Ongoing Activity and Future Plans: The GWPC is in discussions with the Pennsylvania Department of Environmental Protection to develop an electronic reporting system for chemical use associated with Marcellus shale gas development. The Pennsylvania legislature is considering regulations that would require companies to disclose to the state any chemicals used in HF operations. In addition, GWPC is working with states to develop a plan for the national oil and gas gateway, which will enable the Energy Information Administration to receive production and injection data electronically.

Lessons Learned: The suite of tools available through RBDMS provide useful support to the oil and gas offices that oversee field activities related to oil and natural gas development for 22 states and the Osage Nation.

Operators and service companies have been willing to provide the majority of fluid and chemical data related to hydraulic fracturing as is evidenced by the 85,000 well disclosure entries in FracFocus provided by 762 companies. Tracking of operator reporting compliance in FracFocus will begin in 2015 with comparisons to state RBDMS reports.

Due to the significant number of shale wells being drilled, many state agencies required continued support in the areas of defining best practices, inspections, and water tracking which can be provided through continued upgrades and additions to existing RBDMS tools.

The National Oil and Gas Gateway has been created to aggregate oil and gas data while providing a link back to the state agency websites. Currently five states are providing data to the Gateway which is planned to go public in 2016.

Risk Based Data Management System (RBDMS) and Cost Effective Regulatory Approaches (CERA) Related to HF and Geologic Sequestration of CO2—Groundwater Protection Council; 10/2009–9/2016

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Project Number: FE0000880

More information can be found at:

http://netl.doe.gov/research/oil-and-gas/natural-gas-resources/fe00880_rbdms

Or, on the GWPC Risk Based Data Management System website:

http://www.gwpc.org/programs/risk-based-data-management-system

Development of Non-Contaminating Cryogenic Fracturing Technology for Shale and Tight Gas Reservoirs—Colorado School of Mines; 7/2012–7/2015

Objective: Fracturing shale and tight gas reservoirs stimulates hydrocarbon release by creating fractures that increase the contact area between a reservoir and a borehole. Although water is often used in the fracturing process, fractures can also be created by sudden temperature changes, causing thermal contraction of the surface and local tensile stress. This mechanism has not been exploited in the context of stimulation and may be a viable method to weaken or fracture reservoir rocks to reduce or eliminate water usage. Thus, the objectives of this project are to study, develop, and test a novel cryogenic fracturing technology for enhanced gas recovery from low-permeability shale gas and tight gas reservoirs.

Research Planned: Researchers performed numerical simulations to develop a simulation tool for modeling the influence of the cryogenic fracturing process on the artificial fractures of simulated rock. They then developed experimental procedures to conduct cryogenic fracturing tests with and without confining stress, and with integrated cryogen transport, measurements, and fracture characterization. The design involved a tri-axial loading system specifically designed to simulate reservoir-confining stress conditions through the application of stress up to 6500 psi vertically and 4500 psi horizontally. The experiments were repeated with transparent specimens to allow observation and insight into fracture propagation upon the application of sufficient thermal contraction and stress.

Results-to-Date: Cryogenic stimulations resulted in the creation of cracks in experimental blocks and the deterioration of rock properties. Fractures are created along a line corresponding to the strongest thermal gradient in a concrete block that is half-submerged in liquid nitrogen. Increasing the number of cryogenic stimulations creates new cracks and widens the existing cracks. However, a comparison of the cryogenic fracturing results in weak cement concrete and sandstone demonstrated that fracturing is dependent on material properties. More cracks are created near the surface of the weak concrete specimen rather than internally.

Ongoing Activity and Future Plans: Researchers will observe whether thermal shock creates fractures at reservoir stress levels and will investigate how borehole pressurization improves fracturing. The effect of stress on the characteristics of cryogenic fracturing will also be investigated, as will the influence of various material properties on fracturing behavior. Additionally, full dimensional analysis will be performed to further knowledge and ultimately to serve as guide for designing field-scale studies.

Lessons Learned: Results of the study to-date have identified challenges and issues that must be overcome, including reliable transportation of materials to reservoirs, use of proppant with liquid nitrogen, and high heat flux and heat capacity of rocks.

Benefits: This innovative fracturing technology may reduce the kind of formation damage created by hydraulic fracturing and other stimulation methods. Additionally, the adoption of cryogenic fracturing may minimize or eliminate water usage and possible groundwater contamination by fracturing fluids.

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Project Number: 10122-20

This project is ongoing; therefore, the final report is not yet available. However, more information is available at: http://www.rpsea.org/projects/10122-20/

Development and Validation of an Acid Mine Drainage Water Treatment Process—Battelle Memorial Institute; 10/2013–9/2015

Objective: More than 30 billion gallons of freshwater have been used for hydraulic fracturing (HF) since 2011 alone. Since development of unconventional resources is still in the early stages, the demand for freshwater will likely increase in the coming years, taxing local supplies and creating demand for commercial-ready alternative technologies to reduce freshwater usage. The goal of this project is to research and optimize a Floatation Liquid-Liquid Extraction (FLLX) water treatment system. The system will process and repurpose acid mine drainage (AMD) water for use in HF operations and assess the feasibility of using the system byproducts to process produced water. The objectives of this project are three-fold: to develop an innovative treatment process to support the use of AMD water for HF, evaluate the use of FLLX process byproducts in flow back water treatment processes, and determine the environmental, regulatory, and commercial implications of using treated AMD as source water during HF.

Research Conducted: The team has initiated process setup activities at a field demonstration site in Sarver, Pennsylvania and drafted an experimental design plan for bench-scale validation and optimization of AMD treatment process parameters. The project team has also identified stakeholder companies that may benefit from treated AMD water and invited those companies to participate in defining requirements for source water treatment.

Benefits: Large-scale produced water recycling provides producers with significant cost savings, allowing industry to realize lower transportation and disposal costs and fewer environmental conflicts and risks of interruption to well development.

Ongoing Activity and Future Plans: The team will optimize a 3,400-bpd water processing system to provide freshwater from AMD sources for hydraulic fracturing. The immediate outcome will be a commercial-ready system operated by a water services company at a throughput volume useful for HF operations and an optimized technology ready for deployment at additional sites.

Lessons Learned: Project reporting has just begun and no lessons learned have been reported yet.

Key Contact: Anne Lane, Battelle Memorial Institute, 614-424-3266, LaneA@battelle.org

Project Number: FE0014066

More information is available about this project at:

http://www.netl.doe.gov/research/oil-and-gas/project-summaries/natural-gas-resources/fe0014066-battelle

Development of Nanoparticle-Stabilized Foams to Improve Performance of Water-less Hydraulic Fracturing—University of Texas; 10/2013–9/2016

Objective: The overall objective of this project is to develop a new method of stabilizing foams for frac fluids, namely, the addition of surface-treated nanoparticles to the liquid phase. The research will be conducted using fluids already employed in hydraulic fracturing (carbon dioxide [CO2], nitrogen [N2], water, liquefied petroleum gas [LPG]) and commercially available nanoparticles.

Research Conducted: Researchers are conducting foam generation experiments to explain the basis for nanoparticle/surfactant synergy in foam stabilization and developing methods to control pressure on stable, static foam to observe whether collapse occurs at a threshold pressure. Stable CO2-in-water foams were produced in a beadpack using mixtures of surface-modified, commercially available silica nanoparticles and three carboxybetaine surfactants. The team built on this knowledge by generating stable 90 percent quality CO2-in-water foams with the addition of 0.1 percent of partially hydrolyzed polyacrylamide polymer. The team also built conceptual models that predict the stability of bulk foams and foams in porous media under different operating and synthesis conditions with attention being given to the influence of pressure, which is the proposed mechanism for controlling foam destabilization for flow back after fracture stimulation.

Accomplishments: The foams produced as part of this project have much higher viscosity than foams generated with the either the nanoparticles or surfactant alone. This synergy is a remarkable property that had not been demonstrated before. Foams made with the polymer showed a second and distinct synergistic effect: foam cannot be generated until a threshold polymer concentration is reached.

Benefits: Foams have the potential to eliminate 80-90 percent of the water needed during fracturing. The surfactants used to stabilize foam usually degrade in high temperatures, high salinity environments. Using nanoparticle-stabilized foams instead of a surfactant-stabilized foam in the fracturing environment may be the solution. If successful, this project could significantly reduce the amount of water needed for hydraulic fracturing and provide cost and environmental savings.

Ongoing Activity and Future Plans: An apparatus to test N2/NGL (natural gas-to-liquid) foams is currently being designed and constructed.

The team is also writing and testing numerical simulation software that will simulate the propagation of CO2-water bulk foams, stabilized by nanoparticles, with and without surfactant.

Lessons Learned: Work on this project has recently started and no lessons learned have been identified yet.

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Project Number: FE0013723

More information is available about this project at:

http://www.netl.doe.gov/research/oil-and-gas/project-summaries/enhanced-oil-recovery/fe0013723-uta